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Development of Instrumentation for Monitoring Carbon Fiber Emission

TRW Defense and Space Systems Group
Redondo Beach, CA

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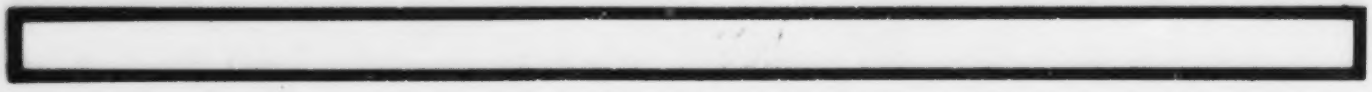

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16. ABSTRACT

This document reports the design of an electrical instrument which utilizes a variable capacitance in one leg of an R-C feedback network to provide discriminatory information regarding the air stream particulate materials. Sufficient testing was performed on the breadboard to validate system concept. The current instrument is counting fiber mass and indicating fiber diameters to yield an approximate count of individual fibers. Its operational range has a lower limit of 10^4 fiber/m^3 and an upper limit internally restricted for this breadboard state to 2×10^8 fibers/m^3. The program scope did not allow completion of a prototype design; therefore, emphasis is placed on recommendations to complete design efforts.

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PREFACE

"Carbon fiber" is a generic term for those carbon-based fibers which have been subjected to a very exacting controlled process to achieve proper stereochemistry via material stretching and high temperatures (e.g., ~1100 to 1200°C for true carbon fibers and ~2500°C or greater for graphite fibers).

Research efforts continue to explore all possible combinations seeking to maximize such physical characteristics as material tensile strength, thermal conductivity, electrical resistivity, specific heat, density, tensile modulus, and elastic recovery. To state that a manufacturer has infinite selection opportunity when selecting structural materials for today's products is an exaggeration; however, these advanced composites do introduce a new facet.

The utilization of these composites began in the aviation and space industries, but quickly spread to the automotive and sporting equipment markets. Weight savings of from 15 to 50 percent are common while achieving superior stiffness, fatigue resistance, improved friction coefficients, and noise reduction. These factors have recently prompted the petroleum, textile, and even precision instrument and medical industries to begin incorporating these advanced composites.

All this seems to substantiate manufacturers' claims that these composites will see a 25 to 40 percent growth rate over this decade.

A significant drawback associated with the carbon/graphite epoxy composites has been identified. Due to their excellent electrical conductivity, if allowed to contact electrical circuits or certain electric components these fibers may cause sparkover, shunts, impedance variations, as well as other phenomena which adversely affect the function of the equipment.

If such fibers are allowed to penetrate vital military and satellite communication systems, or key electrical/electronic equipments in industry, the resultant performance degradation could prove more than annoying and financially prohibitive.

The initial reaction to the carbon fiber issue was to treat it as a new hazard of great damage potential. A Joint Technical Coordination Group comprised of the Air Force, Army, and Navy was formed. Many investigators have performed extensive evaluations over the past two decades and scientists at numerous companies have investigated the behavior and physical characteristics of carbon fibers (CF) via laboratory and field tests.

All this activity has resulted in a vast amount of information pertinent to the performance of CF when exploded, burned, or simply lofted airborne. These studies have shown that only certain scenarios may afford the real carbon fiber threat which was initially feared and that if controlled and properly monitored, any real threat may be easily avoided.

Pursuant to the military action, a U.S. Government interagency task force was formed; as a member of this task force the EPA has been concerned with monitoring ambient concentrations of CF. The bench mark for monitoring CF emissions is sampling followed by microscopic counts of the collected fibers. This is a time-consuming task whose results are neither real-time nor continuous.

Anticipating the intense growth of the industrial utilization of these CF composites, the EPA in the 1970s began seeking a means to continuously monitor these emissions. R&D efforts began with an evaluation of existing instrumentation and efforts which would refine these methods to provide a continuous real-time monitor of the number, mass, and size-distribution of carbon fibers emitted from the source operation.

ABSTRACT

Anticipating the intense growth of the industrial use of advanced composites which utilize carbon/graphite fibers as their reinforcing material, this program was concerned with the development of instrumentation that could monitor effluent air streams for carbon/graphite fiber. This instrument should then provide a real-time, continuous output of mass and fiber length as well as other parameters of such emissions.

This document reports the design of an electrical instrument which utilizes a variable capacitance in one leg of an R-C feedback network to provide discriminatory information regarding the air stream particulate materials. Sufficient testing was performed on the breadboard to validate system concept. The current instrument is counting fiber mass and indicating fiber diameters to yield an approximate count of individual fibers. Its operational range has a lower limit of 10^4 fibers/m^3 and an upper limit internally restricted for this breadboard stage to 2×10^8 fibers/m^3. The program scope did not allow completion of a prototype design; therefore, emphasis is placed on recommendations to complete design efforts.

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SECTION 1

INTRODUCTION

OBJECTIVES

The Environmental Protection Agency (EPA) has been charged with the responsibility to document and research the possible instrumentational techniques for continuously monitoring carbon fiber particulates. The activity described herein was in performance of Phase II of a two phase program designed by the EPA to partially fulfill this task. The objectives of this program were:

In Phase I

- To evaluate existing instrumentation and instrumentational techniques for the capability of monitoring carbon fiber emissions.

In Phase II

- To refine this instrumentation to yield a more discriminating sensor, or, if such instrumentation did not exist
- Develop instrumentation for monitoring such CF emissions.

Two implied tasks, necessary in order to approach these objectives proficiently were 1) identify those environments deemed to be of questionable threat potential, thus requiring continuous monitoring; and 2) once identified, determine the parametric conditions of these environments; hence, identifying the proposed operational ranges for the monitoring equipment.

As indicated above the identification of the potential threat to the environments fell into the Phase I work package along with the evaluation of existing instrumentation and selection of the best method for further development. Detailed accounts of these findings are found in References 1 and 2. However, to provide continuity those key findings of Phase I activity which impact Phase II are summarized here.

SUMMARY OF PHASE I FINDINGS

The contractors involved in Phase I activities failed to reach a consensus as to the existing instrumentation which might be utilized for further study. They did agree, however, that the target working environments would be in two principal areas: CF manufacturing and waste disposal.

If we define a carbon fiber episode as any incident when carbon fibers of an undesirable length and concentration are released into the atmosphere, then the first environment which might produce a CF episode is manufacturing. In the manufacturing setting a CF episode may occur in a) the production line for mat fibers immediately following the carbonization process, b) in work areas where these mat fibers receive further processing, or c) in collective exhaust emissions for all processes and vented work areas (Reference 1).

The very rigid control requirements of the processing sequence result in the actual potential for a CF episode during manufacturing processes to be small. During production, the fibers are in a vacuum or gaseous environment (i.e., nitrogen, cyanide, etc.) whose exhaust fumes are properly controlled. When raw fibers are being worked, the area is vented. These hood exhausts then undergo proper treatment prior to discharge. Past practices have dictated that manufacturers working with raw carbon fibers tolerate only minimal fugitive emissions. Concentrations at or below those shown to be a potential electrical hazard ($\geq 10^4$ to 10^7 fibers sec/m^3) (References 1, 3, 4) become irritating to worker's skin, nasal passages, eyes, etc. GCA reports (Reference 1) that anticipated exhaust volume and velocities for at least one manufacturer are as depicted in Table 1.

TABLE 1. MANUFACTURING AND PROCESSING CF EMISSION SOURCE ENVIRONMENTS

Source	Exhaust Volume	Velocity	Abated Exhaust
Mat Fiber Production Line	7.1 m^3/sec	15.3 m/sec	Yes/Rotary Drum
CF Mat Fiber Work Area Exhaust	3.78 m^3/sec	6.1 m/sec	Yes/Rotary Drum Bag House

The second environment which presents the potential of a CF episode is that of waste disposal. The greatest threat potential reported (References 1, 2) arises in conjunction with the incineration environment.

Due to their development processes, CF composites are extremely resistant to combustion. Studies indicate that their fate would be related to the operational parameters of the particular burn. Electron micrographs reveal that the CF matrix is first degraded, leaving the individual fibers essentially undisturbed (Reference 5). Raw fibers (e.g., those which have not been prepregged) will show signs of pitting within 2 to 5 minutes of 1000°C temperatures, but little further degradation follows. Prepregged fibers, subjected to the same conditions, first lose their matrix (occasionally leaving clinging charred epoxy on the surface of the newly exposed fibers), but no significant destruction of the fibers will occur (Reference 6).

Studies involving explosion and/or burn scenarios indicate that the individual fibers released during these scenarios have an affinity for fractioning during the combustion and transport action, thus yielding fibers of 2 to 10 mm lengths (Reference 7).

Consequently, it is desirable to develop an instrument which could be placed in an incinerator stack to monitor the particulate effluent. While assuming the quench water and APCDs (air pollution control devices) will remove some of these fibers, as loading increases it must be assumed that their potential escape is evident.*

It is, therefore, advantageous that the CF continuous monitor provide real-time data on concentration and mass distribution of carbon fibers present in the gaseous effluent from the two environments.

As previously stated the Phase I contractors concluded that although several existing monitors have been utilized in the past, no one existing instrument could satisfactorily accomplish the intended task. Table 2 reviews a few of those instruments evaluated. (For more complete details, see References 1 and 2.)

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*In a separate effort, the EPA is seeking to identify those combustion parameters which would most successfully destroy carbon fiber.

TABLE 2. ATTRIBUTES AND LIMITATIONS OF EXISTING TECHNIQUES FOR ACTIVE INSTRUMENTATION (1,2)*

Method	Attributes/Limitations
1. High Voltage Spark	Limited to fibers longer than 1 mm; lose sensitivity with increased concentration.
2. Low Voltage Spark	Less reliability than high voltage; decreased sensitivity when fiber collects on grid.
3. Low Voltage Grid	Highly unpredictable; moisture interference.
4. High Voltage Grid	Highly unpredictable; moisture interference.
5. Lidar	Nonfiber, carbon specific; beam alignment maintenance of clean lens difficult.
6. Brass Ball (BRL)	Sensitive to soot and humidity;
7. Spark Spectrometry	Provides carbon specificity; same disadvantages as spark methods.
8. Microwave	Instrument vibration and dust sensitivity; sensitivity decreases with decreased concentrations.
9. Optical LED	Non-CF specific and decreased sensitivity in low concentrations.
10. Optical Scattering-FAM	Not suitable for collecting clumps or bundles.
11. Optical Scattering-Rotating Lens	Questionable durability in environment.
12. Spectrophone	Elaborate; shows some promise.
13. Radar	Limited to high concentrations and absence of other particulates.
14. LISMEFA**	Adaptable if used in conjunction with carbon specific technique.

*Modifications of these principal detection techniques are numerous, this is not an all-inclusive list.

**Light scattering modulation by electric field fiber alignment and rotation.

TABLE 2. ATTRIBUTES AND LIMITATIONS OF EXISTING TECHNIQUES FOR ACTIVE INSTRUMENTATION (1,2)* (CONCLUDED)

Method	Attributes/Limitations
15. Photo-thermal Detection and Electric Alignment (GCA)	Mass productions unit could prove expensive; requires skilled operator.
16. OSGEF-Microwave (ADL)	No experimental data available to verify operational aspects.

In summary Phase I activity succeeded in identifying the potential threat environments and, thus provided operational parameters for a successful continuous monitor. This effort also concluded that new instrumentation which could more adequately meet the intended functional demands must be developed.

A study of the existing instrumentations' attributes and limitations revealed that the CF conductivity is one of the more sensitive and reliable physical parameters on which to base instrument design. This document then reports the design and testing of one such electronic device fundamentally utilizing a change in capacitance (ΔC) and resistance (ΔR) produced by this parametic state.

SECTION 2

CONCLUSIONS

Based on studies performed to date, it must be concluded that there is no single monitoring device which will function in the targeted environments (i.e., manufacturing and processing, and incineration waste disposal) to continuously provide real-time data for all those elements of the ideal CF monitor.

The instrument whose design is provided herein is not the completed design; however, if refined could provide meaningful data.

Laboratory tests indicate an electronic device which measures the capacitance change resulting from the presence of conductive carbon fibers shunted across the plates of a variable capacitor could prove worthy of further development.

The existing breadboard instrument is counting fiber mass and indicating fiber diameters to yield an approximate count of individual fibers. Its operational range has a lower limit of 10^4 fibers/m^3 and the upper range is restricted to a maximum of 2×10^8 fibers/m^3 by the internal constraints place in the system for testing convenience.

Fiber lengths are currently being indicated as relative to mass and the ring spacing by the effect of ΔC versus ΔR. Section 6 contains the method which if included would indicate fiber length.

SECTION 3

RECOMMENDATIONS

Laboratory tests have proven the sensor is capable of detecting carbon fibers. However, the design of the electrical circuit is not functionally complete. It is a breadboard designed to provide verification of concept feasibility. The level of sophistication desired will dictate the extent of further development. Many of these issues are dealt with in Section 6.

At a minimum, four modifications and additions are required to complete the breadboard to a first stage prototype design. They are as follows:

a. Self-cleaning mechanism — A high voltage discharge sufficient to arc the adhering particulate matter is suggested.

b. Internal measurement of the C and R values which lead to the variable capacitor's frequency shift — These internal self-measurement circuits are standard and easily implemented.

c. Proper material selection to ensure the sensors survival in the target environments — The use of ceramic spacers in the variable capacitor, etc. A more aerodynamic design for these spacers is also suggested.

d. Frequency/voltage (F/V) chip — Replace the present F/V converter with one of a broader band and remove the internal constraints placed on the circuit at C_6 and C_7. These features were utilized during testing; sequential stages of instrument development should remove them to allow a higher upper limit.

Following the above suggested modifications the instrument should be designed as a self-contained unit (i.e., provided with its own power supply, readout device, reference oscillator, etc.). No special requirements are presently indicated and no unusual problems are foreseen.

After obtaining a self-contained unit, the instrument should be tested over varying environmental conditions (temperature, humidity, dust, vibration, corrosions, etc.). Testing to calibrate the unit should include varying concentrations, fiber length, and CF types to reduce the error potential due to different chemical features of carbon fibers.

SECTION 4

INSTRUMENT DESIGN

PROGRAM APPROACH

Studies failed to reach a consensus on the most promising continuous, real-time monitor for the targeted environments and parametric conditions (References 1, 2). It was necessary, therefore, to critically review past CF activity and instrument performance for concept applicability because recent advances in electrical and electronic equipment have significantly increased the capabilities and signal-to-noise ratio (therefore, discriminative sensitivity) of instrumentation.

Table 3 presents some of the instruments which were utilized by TRW in previous CF tests. Table 4 discloses advantages and limitations, to these methods as well as others reviewed. All of this information was integrated with the findings of Phase I activity (References 1 and 2).

It was concluded that recent electrical improvements were not of sufficient magnitude to offset inherent limitations or justify further development of the existing instruments; however, certain instrument characteristics could certainly be capitalized.

It was determined that no one method could meet all desired operational parameters and since present methods encountered considerable objections, it was apparent that two options were available.

a. Take advantage of the most sophisticiated electronic data reduction schemes, advanced sampling, and microprocessing capabilities to develop a state-of-the-art sensing device, or

b. While keeping in mind the instrument's proposed use, develop a new system which would provide the most information possible, utilizing the resources presently available.

The first option would involve extensive R&D and material cost, thus limiting the work effort to electrical and instrumentation design. The project would therefore yield only an untried instrument. In the best judgment of the scientists and engineers involved, such a sophisticated system would be expensive, delicate, and require a skilled operator. It

TABLE 3. TRW EXPERIENCE WITH CONTINUOUS MONITORING SYSTEMS FOR CARBON AND KEVLAR FIBERS

FACILITY \ DETECTOR	LIGHT EMITTING DIODE	LASER	MICROWAVE HORNS	MICROWAVE ROD	HIGH VOLTAGE GRID	HIGH VOLTAGE BALL	IR IMAGING CAMERA	MICROWAVE RADAR	ULTRAVIOLET LADAR	RUBY LADAR	ACOUSTIC SOUNDER	L.C. DEPOSITION	SPECTROGRAPH	MAGNETOMETER (LOW FREQUENCY)
1976 BOEING AIRCRAFT CORP. CF TEST CHAMBER	•	•	•											
1976 OTIS AIR FORCE BASE	•	•	•											
1977 TO 1979 ROME AIR DEVELOPMENT CENTER	•	•	•	•		•								
1978 TRW CAPISTRANO TEST SITE	•		•		•	•								
1978 NAVAL WEAPONS CENTER	•		•		•	•	•			•		•		
1978 CLEAR LAKE, CA, TEST SITE							•	•	•		•			
1979 HILL AIR FORCE BASE	•						•		•					
1979 TO 1981 TRW LABORATORY AND MANUFACTURING FACILITIES	•	•	•			•	•	•	•	•		•	•	•

TABLE 4. APPLICABILITY AND LIMITATIONS OF EXISTING INSTRUMENTATION

	Sensor System	Applicability (Advantages)	Limitations
In Cloud Active Detection	1) Zapper, high voltage (Mitre)		High entrainment velocities cause fibers to align improperly
	2) Ball gauge, high voltage	Fiber concentration and length data	Instability in high humidity, temperature. Reads all conductive fibers
	3) LC (inductance, capacitance) gauge		Not CF specific
	4) Light emitting diode		Not CF specific; light and temperature sensitive
	5) Microwave attenuation	Fiber length data function of system frequency, etc. Insensitive to non-conductive particles	Sensitive to vibration; enclosed areas backscattering a problem (calibration problems; cost)
Remote	6) Infrared scanning	Excellent for gross plume measurements	
	7) Ultraviolet radar		Vibration, dust, non-CF specific problems
	8) Microwave radar		Vibration, dust, non-CF specific problems
Post Activation	9) Iridium tagging		No real-time data unless samples preexposed

would still possess objectionable features. The instrument could prove useful for test facilities or providing calibration and baseline data; however, it would not fulfill the intent of the contract.

Therefore, it was agreed to embrace Option b., thereby maximizing work effort to provide a practical instrument relative to its function and operating environment. A secondary objective was established to demonstrate that an inexpensive electronic circuit could be developed which could provide much of the needed information required of a CF continuous monitor. It has never been the intention of the design engineers to advance the present design to a final design prototype at this time. Further development and refinement are necessary to ensure reliability and durability.

CONCLUSIONS LEADING TO CONCEPT DESIGN

The preliminary concept of a resistance-capacitance (R-C) feedback network utilizing a variable capacitance in one leg of two stable "twin-tee" oscillators was selected for development. This selection was based on a) information gathered regarding the capabilities/limitations of existing instrumentation (Tables 2, 3, and 4); b) desirable aspects of an 'ideal' monitor (Table 5); and c) known operational environments (the target environments — manufacturing and processing, and incineration waste disposal).

Key elements which surfaced were:

- CF's physical parameter of conductivity was the most discriminating basis.
- All aspects of an ideal monitor (Table 5) could not be dealt with by one single instrument.
- Priority need be placed equally on instrument ____
  a. Versatility
  b. Environment ruggedness
  c. Reliability
  d. Automatic, continuous, real-time output
  e. Specificity to conductive fibers (defining a fiber as a particulate material with an aspect ratio of 1:5).

The proposed operational environments indicated that the sensor must tolerate dust, vibration, temperature variations, moisture fluctuations, caustic chemicals, and hot gases.

TABLE 5. CONSTITUENT FEATURES OF THE 'IDEAL' INSTRUMENT

Descriptive Elements of Proposed Instrument	Desirable Feature	Basic Requirements
1. Continuously monitor for CF emissions (mass, fiber length, fiber concentration)	•	•
2. Provide real-time output	•	•
3. Automatic/adjustments, threshold impulses, count, etc.	•	
4. Self-cleaning	•	
5. Differentiates carbon fibers from particulate carbon, carbon black	•	•
6. Differentiates CF from other aerosol particulate fibers	•	
7. Versatile rugged, durable		
a. Withstands wide variations in temperature and humidity	•	•
b. Withstands corrosion, dust, vibration		
8. Accurate (compared to passive monitors), reproducible, sensitive, good response time, wide operational range	•	•
9. Stability	•	•
10. Low detection limit (as a minimum 10^4 to 10^7 fibers/m^3)	•	•
11. Ease of installation; some degree of portability	•	

TABLE 5. CONSTITUENT FEATURES OF THE 'IDEAL' INSTRUMENT (CONCLUDED)

Descriptive Elements of Proposed Instrument	Desirable Feature	Basic Requirements
12. Alarm system capability	•	
13. Low false alarm rate	•	
14. Candidate for mass production	•	•
15. Reasonable size, weight	•	•
16. Record capability	•	
17. Low cost to manufacture, install, operate, maintain	•	•
18. Minimal amplifier drift	•	
19. Compensatory to aging and unattended use	•	

Experience in instrument development indicated that it would prove expedient to separate the sensing device from the discriminator, thus exposing only the sensor to the harsh environmental conditions. This could also increase the ease of installation and degree of portability of the instrument.

The design philosophy shaped by these elements concluded that the R-C feedback network could prove acceptable. The reference oscillator was provided to promote temperature stability and further design modifications were made to enhance the sensitivity of the instrument.

INSTRUMENT DESCRIPTION

The electrical diagram for the existing design at the time of final testing is in Figure 1. The circuit's component parts list and peripheral equipment are shown in Table 6. Sections 3 and 6 express the extent of refinements and expanded testing which remain.

The carbon fiber monitoring system is a frequency shift device. The sensor acts as a variable capacitance in one leg of an R-C feedback network (Figure 2). The frequency at which a 180 degree phase shift takes place across the R-C feedback network is the frequency of oscillation. A reference oscillator provides the second waveform, thus two stable R-C ("twin-tee") oscillators' waveforms are fed into a detector system which outputs a difference frequency. This difference frequency is fed into a frequency to voltage (F/V) converter which produces a direct continuous voltage output that is proportional to the capacitance variance (this is, the fiber concentration).

The difference between the reference oscillator and the sampling oscillator is that the sampling unit utilizes a unique air dielectric capacitor in its frequency feedback circuit (Figure 2). This unit consists of concentric rings (plates) constructed in a manner to allow gaseous flow through it. Therefore, conductive impurities in the gaseous flow will produce the above mentioned phase shift. The reference frequency is provided by an identical oscillator which utilizes a fixed capacitance. This approach provides good temperature stability.

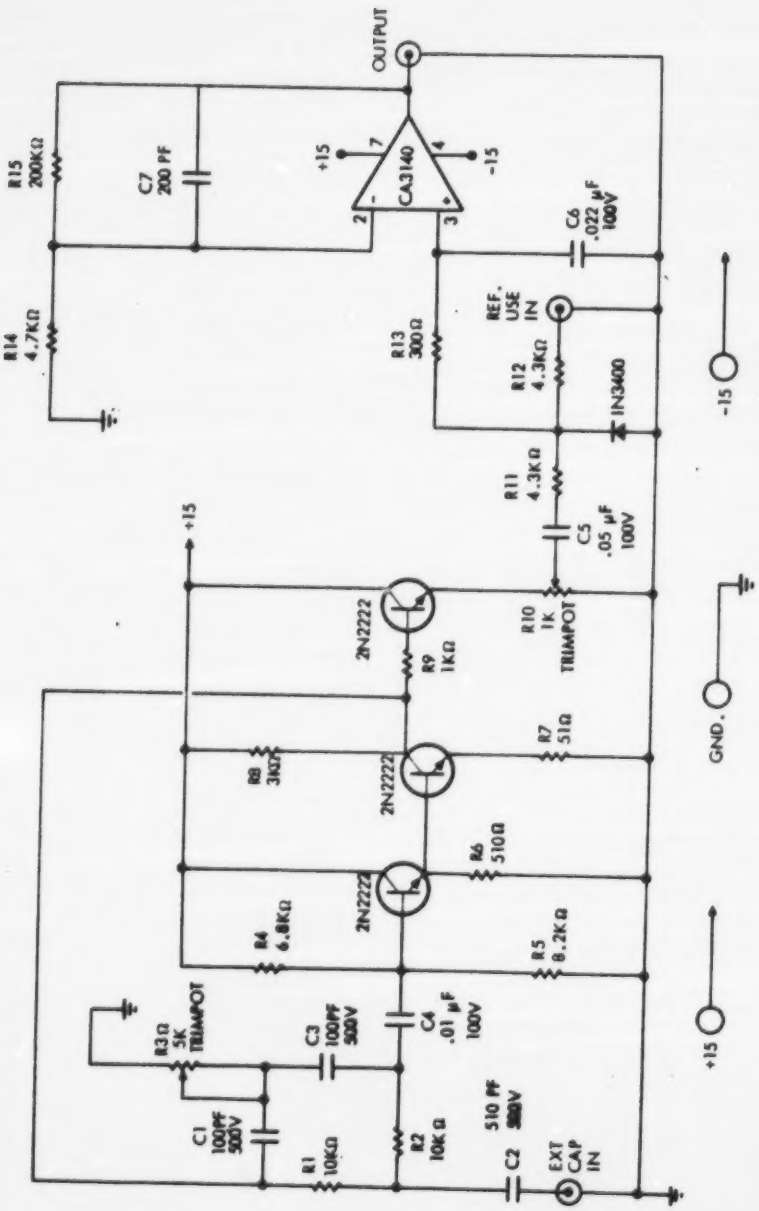


Figure 1. Electrical diagram.

TABLE 6. PERIPHERALS AND COMPONENT PARTS LIST

Instrumentation	Capacitors	Resistors	Diode
Tektronix Scope 7844	MICA FIXED	R1-10K, 1/10 W, Metal Film	IN 3400
	C1 100PF 500V	R2-10K, 1/10 W, Metal Film	
HP Signal Generator 606A	C2 510PF 500V	R3-5K Tenturn Trimpot	3 ea BNC Connector Chassis
	C3 100PF 500V	R4-68K 1/2 W Carbon	3 ea Pin Jack Connector
HP Electronic Counter 5245L	CERAMIC FIXED	R5-8.2K 1/10 W Metal Film	1 ea 8 Pin Socket for CA3140
		R6-510Ω 1/10 W Metal Film	1 ea OP HMP CA3140
HP Strip Chart Recorder 71018	C4 0.01μF 100V	R7-51Ω 1/10 W Metal Film	3 ea Transistor 2N2222
	C6 0.022μF 100V	R8-3K 1/4 W Metal Film	
Sangamo Tape Recorder SABRE VI	CERAMIC DISC	R9-1K 1/10 W Metal Film	
	C5 0.05μF 100V	R10-1K Tenturn Trimpot	
		R11-4.3K 1/10 W Metal Film	
		R12-4.3K 1/10 W Metal Film	
		R13-300 1/10 W Carbon	
		R14-4.7K 1/10 W Metal Film	
		R15-2.00K 1/10 W Metal Film	

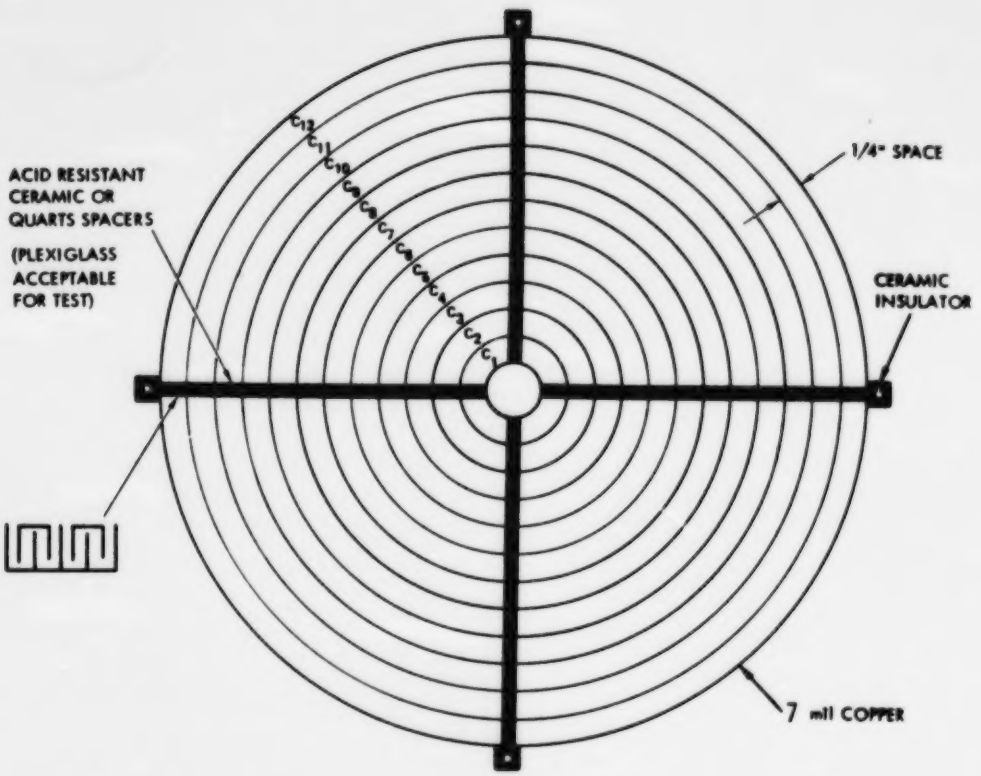


Figure 2. Arrangement of variable capacitor.

The sensing capacitor is so designed that it may be suspended in an incinerator stack or vent ducting. The remaining circuitry may then be more conveniently located. This feature decreases size requirements (thus disturbance in airflow, due to the location of the device in the air stream).

To summarize, the reference oscillator and the 'sensing' oscillator input an identical (or harmonic) frequency to the detector system. The detector mixes the two frequencies. At this point the detector outputs a deference frequency, which is tuned to be zero when no CFs are present. When CFs enter the sensor, they change the characteristics of the dielectric (i.e., air) resulting in a change in capacitance of the sensor proportional to the degree of change in the conductivity of the CFs (relative to air) as CFs form shunts across the capacitor plates. With the change in capacitance the waveform is changed to the frequency at which a 180 degree phase shift takes place across the R-C feedback network. This frequency is now the frequency of oscillation of the sensing capacitor's R-C network.

The new frequency is then mixed with a reference, and a difference frequency ($f_1 + f_2 = f_3$) is input to an F/V converter. The output from this chip is a direct continuous voltage output which is proportional to the degree of change in the sensing capacitor (thus proportional to the conductive fiber concentration).

One modification to the original design circuit should be noted. Minor changes were made in the electronic circuit from the original design to allow the use of a bandpass filter and frequency to voltage converter which was preconfigured. This made it necessary to alter some of the values in the circuit. It is suggested that the prototype design possess a wider band and improve on the F/V convercer to allow a broader operational range. The existing F/V allowed a (0 to 10 Volt)/(1 Hz to 10 kHz); however, internal circuit restrictions would not allow the circuit to "see" greater than 2 x 10^8 fibers. While sufficient for the scope of this test program, such limits would not be acceptable for a prototype design.

SECTION 5

INSTRUMENT TESTING

Instrument testing was accomplished in two discrete sequences. Standard development testing paralleled the breadboard development and fabrication tasks and was concluded by a pretest performed to confirm concept design. The second testing was the final breadboard test to establish the capabilities and limitations of the instrument. This test series was performed at the conclusion of the project.

The test layout and sequence were kept simple and straightforward. The intent was not to conduct a quality comprehensive test series, but to obtain definitive evidence which would allow at least partial verification of answers to the following questions.

a. Are individual fibers counted?

b. What is the device's operational range?

c. Can fiber lengths be established?

d. How small/large spacing can be used?

e. How does the sensor's diameter reflect the electronics sensitivity?

f. How does this diameter/sensitivity relationship relate to the plate spacing and fiber lengths?

g. What happens to the sensor with no care and maintenance?

h. Will condensation affect its operation?

i. Is a cleaning process necessary?

FABRICATION AND DEVELOPMENT TESTS

Figure 3 displays the initial "chamber" used to test the CF monitor. A known mass of fibers was placed in the chamber, and a simple squirrel cage fan generated fiber movement (chamber turbulence). Knowing the internal volume of the chamber and observing the distribution of the fibers, gross measurements verified reference circuit performance figures.

The variable capacitor used as the 'sensor' was constructed of 7 mil copper according to the dimensions provided in Figure 2. The spacers were made from Plexiglas (because of its ease of milling characteristic).

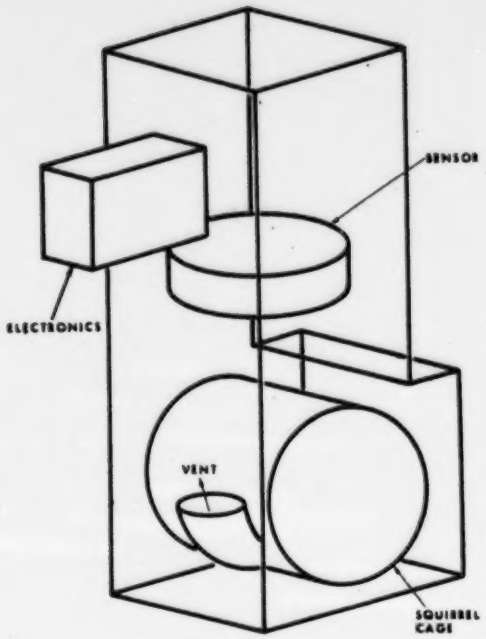


Figure 3. Initial test chamber design.

Alternate concentric circles were connected to provide the two plates comprising the capacitor.

Jacks embedded in the Plexiglas then allowed quick connection to the electronics. The product component (PC) board was in a box (approximately 4" x 5" x 1-1/2 inches) which attached easily to the side of the chamber (see Figure 4). This box in turn connected to the peripheral equipment, as shown in Figure 5. This configuration was consistent for all tests.

The chamber shown in Figure 3 was modified into a recirculating system; however, the inability to identify all particle loss, thereby failing to maintain defined exposure levels of carbon fibers, prompted the redesign of the system to a simple gravity fall-through chamber (Figure 6). Figure 7 shows the instrument arrangement for final testing.

No attempt was made to control the environment in the test chamber. All tests were performed at existing room temperature, pressure, and relative humidity.

Close-up of suspended 'sensor'

Figure 4. Initial test chamber utilized for concept validation.

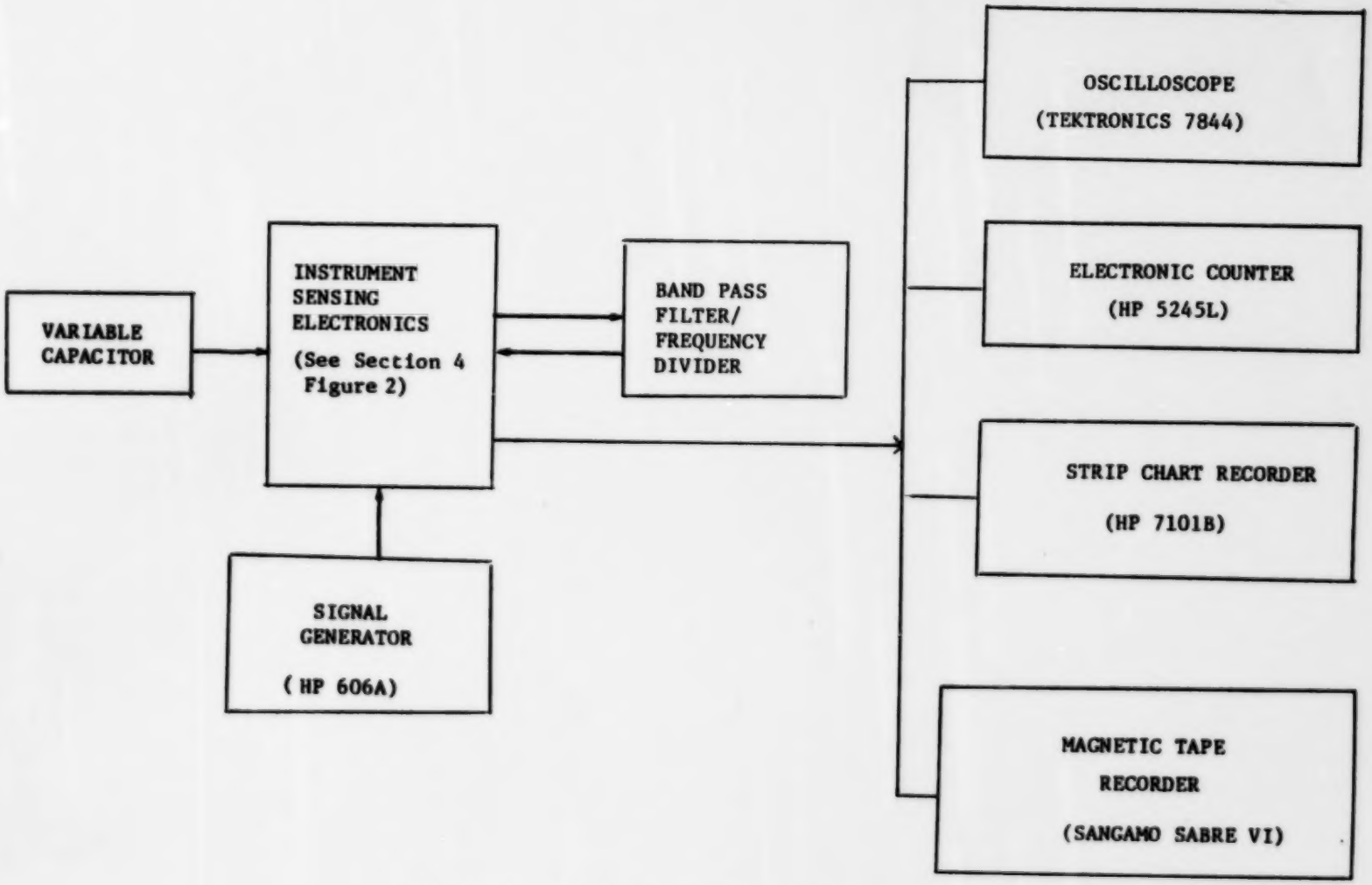


Figure 5. Equipment configuration.

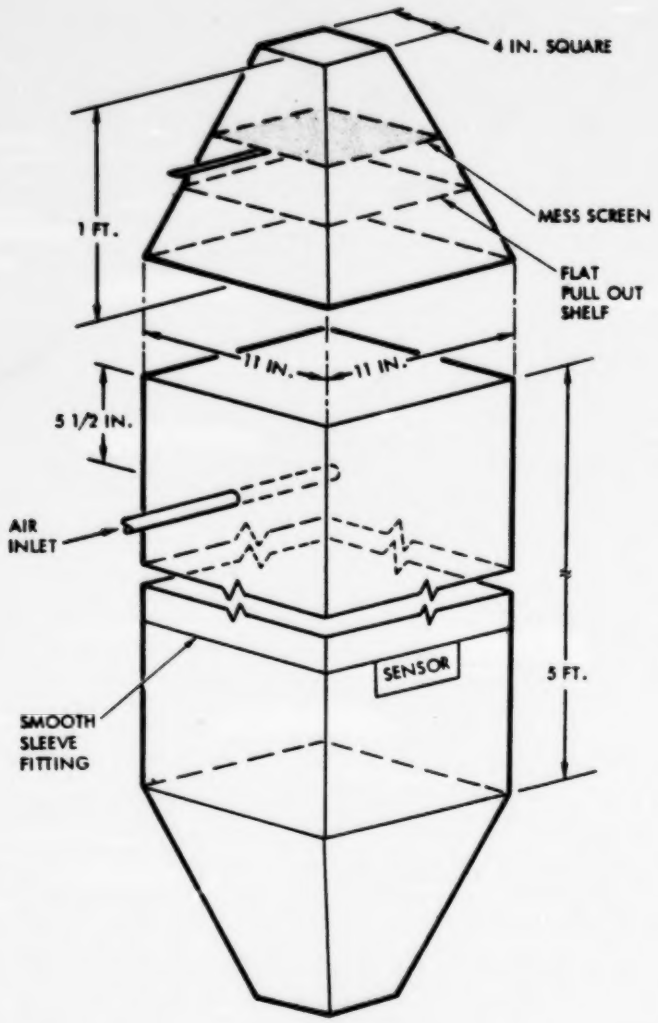
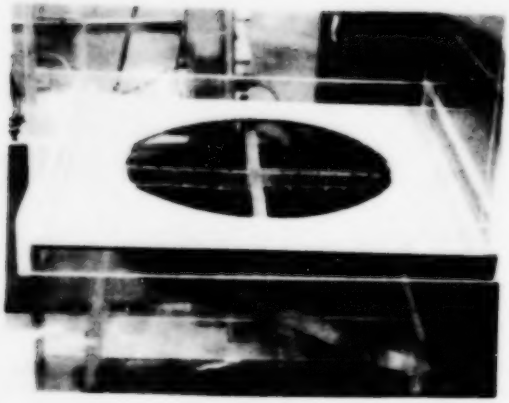


Figure 6. Gravitational settling test chamber.

a. Test chamber assembled with air gun in place.



b. Air dielectric capacitor.

Figure 7. Assembled test chamber and close-up of sensor.

FIBER CLUMPING

A significant problem which surfaced during instrument testing was clumping of the chopped fibers. The carbon fibers used to test the sensor were purchased from Union Carbide Corporation. These fibers were chopped by Union Carbide to specified lengths prior to shipment. By the time the fibers were received they had already established electrostatic bonds. Therefore, the fibers were clumped together in balls of approximately $<10^{20}$ fibers and seemed intent upon remaining that way.

Since the instrument test required that the fibers pass through the sensing capacitor as discrete entities, problems were encountered trying to determine the number and length of the clumped fibers passing through the sensor. One reason attributed to this clumping phenomenon was that the CFs were sized prior to being chopped. Sizing is a generic term for a chemical substance used on carbon fibers to promote flexibility, reduce interfiber abrasion, and increase filament adherence. Unsized fibers were required, however, the manufacturer could not deliver in the required timeframe.

Another possible contribution to the fiber clumping problem was the period of time the chopped fibers were allowed to "cure" during shipment. This allowed the fibers to establish electrostatic bonds and possibly weak H-bonds.

Efforts to eliminate fiber clumping centered around the removal of the sizing from the fibers and the decrease in the electrostatic forces associated with the fibers. Although seemingly straightforward, this task proved challenging. The CF clumps were well established and proved resistant to wetting. Several solvents were used to generate slurries with the carbon fibers which were subsequently mechanically agitated in order to break up the clumps into single fibers. It was then necessary to dry the fibers in an antistatic atmosphere.

Of the various surfactants and solvents utilized, including water, the most effective was the mixture of acetone and water. In the proper combination, it appeared that the acetone performed not only as a solvent but as a wetting agent to release the bubbles trapped between the fibers. The water presumably acted as a solvent for the sizing agent as well as a vehicle for the antistatic compound.

As the slurries were dried, the large clumps were gently mechanically dispersed into smaller groups of fibers. Such care was taken in an attempt to prevent excessive fiber breakage. After drying, the fibers were weighted and placed in the "gun."

A "gun" was designed to create turbulent airflow through a series of screens, thus injecting the fibers into the test chamber. Figure 8a displays the first configuration of the gun. Attempts made to inject the untreated fibers into the chamber were unsuccessful and the results are shown in Figure 8b. Following the removal of the sizing by the above procedure, the gun retained numbers of fibers which could not be distinguished by mass weightings.

Several tests were performed to ensure that the fibers would exit the gun and remain aloft for a brief time while the airflow was still being injected into the chamber. Following the discontinuance of the airflow, the CFs were timed to verify the calculated settling rate. This was necessary to ensure that the CFs arrive at the sensor as a cloud of predictable fiber concentration. During these tests it was determined that with 20 psi of air pressure applied to the gun for 30 seconds, the injected fibers would settle undisturbed.

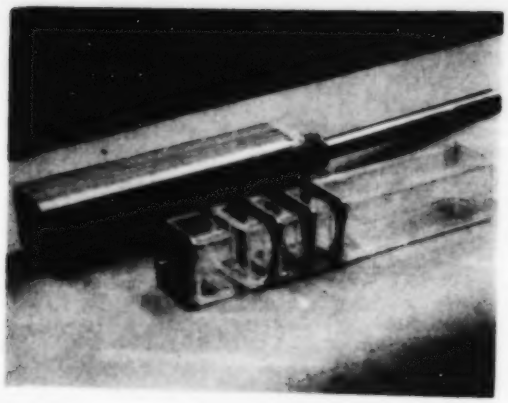
A slight modification was made to the gun at this point and this is shown in Figure 8c and d. Two screens (bridal veil) were removed and a funnel type opening was made aft of the air inlet.

These efforts produced a uniform dispersion of single fibers at the sensor (Figure 9). Tests made by utilizing sticky paper above and below the sensing capacitor demonstrated that essentially no fiber clumping persisted at either location.

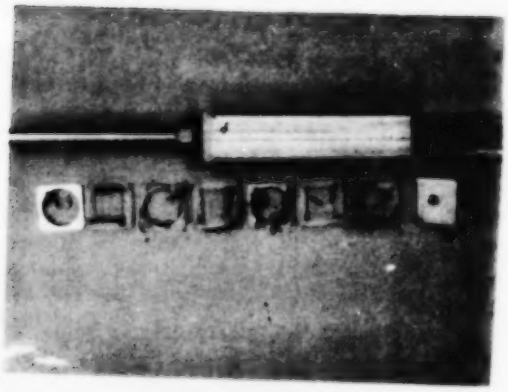
TEST PROCEDURE

The test procedure which was established and maintained throughout all final testing was recognized to provide a degree of inherent error. However, since the intent of the test was only to validate concepts, the procedures were considered adequate.

Following the treatment of the fibers, the sequence presented in Table 7 was begun. The carbon fibers loaded into the gun were first weighed. The gun was loaded, positioned, and the instrument tuned. Airflow was then initiated. Carbon fibers were injected into the system followed by the subsequent steps provided in Table 7.

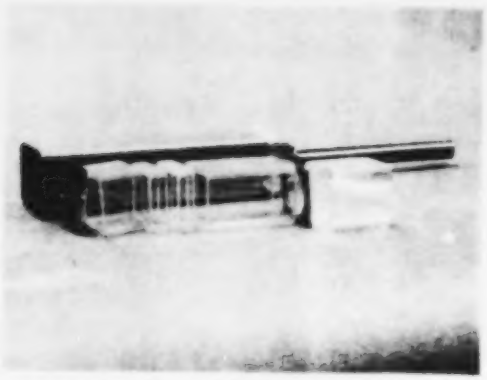


a. Initial three screen configuration.

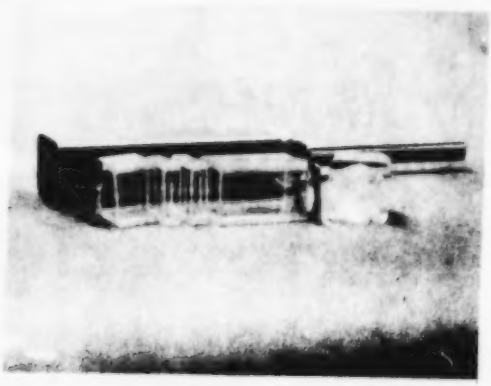


b. Accumulation of untreated fibers in the "gun".

Figure 8. Carbon fiber injection system ("gun").



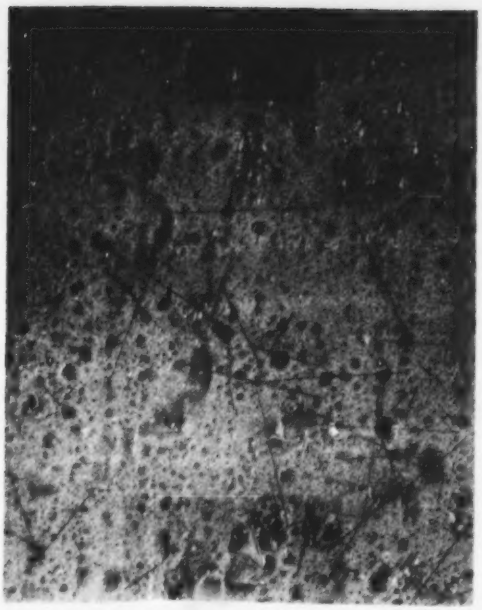
c. Final configuration.



d. Note, funnel shape just aft of screen.

Figure 8. Carbon fiber injection system (continued).

Test run 81/23-4
Note, no fiber clumping.



Test run 81/23-5
Note, high concentration of fractures CF.

Test run 81/23-2
Immediately below sensor.

Figure 9. Microscopic enlargements (10X) of carbon fiber dispersion.

TABLE 7. TEST PROCEDURE

Test Procedure	Time
1. Establish loading mass of carbon fibers	——
2. Initiate airflow	——
3. Final adjustments to sensor	——
4. Begin CF injection into airflow	0 sec
5. End CF injection	30 sec
6. Stop airflow	45 sec
7. Discontinue tests	300 sec

It was assumed that following discontinuation of the CF injection (and thus airflow) the fibers would settle in a reasonable facsimile of a uniform gravitational settling, as previously mentioned.

This expected settling velocity allowed the chamber to be constructed so calculations could be easily made, uniform distribution could be assumed, and no major changes would be necessary to the electronics by altering the plate numbers in the variable capacitor.

Immediately below the sensor was a strip of sticky paper which, while allowing the fiber cloud to pass through the capacitor undistributed, sampled a known area of the CF cloud. At the bottom of the chamber all fibers were collected on a glass fiber filter. A shield around the sensor caught all fibers not passing through the monitor. These numbers could all be utilized to calculate with reasonable accuracy the concentration of the fiber cloud. It also eliminated the uneven distribution (settling) at the chamber walls.

Based on a known loading mass, and the mass obtained by both passive filters following the sensor, the CF concentration could be obtained when coupled with the known settling velocity and chamber volume (excluding that caught on the shield upstream of the sensor). In early runs a gravimetric method was utilized (corrected by moisture curve analysis performed concurrently with the test), but once fiber counts established the negligible fiber loss during a test run only the counts were performed.

To decrease the effects of an electrostatic force between the fibers and the walls of the chamber, it was periodically treated with a surfactant and antistatic agent.

As expected, the distribution of fibers through the sensor showed no evidence of pressure disturbances or altered flow distribution. Throughout testing the fiber patterns confirmed this assumption.

The actual arrival times of the fibers at the sensor did, however, depart slightly from the projected settling velocities depicted in Figure 10 (Reference 1). Their arrival time, t_{ARR}, displayed a direct correlation to the mass concentration released as well as the fiber length distribution. Figure 11 illustrates the fiber arrival times versus total fibers for Test Runs numbers 81/23-1 through 81/23-4. The fiber length distribution for these test runs is presented in Table 8.

CARBON FIBER SOURCE

The carbon fiber source selected for testing was Union Carbide's "Thornel" 300, grade WYP 6-1/0 fibers. This fiber was selected because it is the constituent of 85 percent of all the carbon fiber composites in the marketplace today. The Technical Information Bulletin pertinent to the fibers utilized is provided in Table 9.

Additional tests should be performed with other fiber types/precursors to determine their effect. A waste stream monitor would have to be calibrated to make adjustments for the varying conductivity, density, etc., of varying CF sources.

The initial tests performed on the sensor during development stages utilized various Hercules and Celanese fibers as well as other noncarbon conductive fibers. These fibers varied vastly in fiber length (~6 mm to 3 cm) and were not uniform single fibers, but clumps and single fibers combined. Several of these fibers were prepregged. Results from these fiber tests did not differ noticeably from those obtained during final tests; however, the first tests were not as well controlled, therefore no quantitative conclusions could be made.

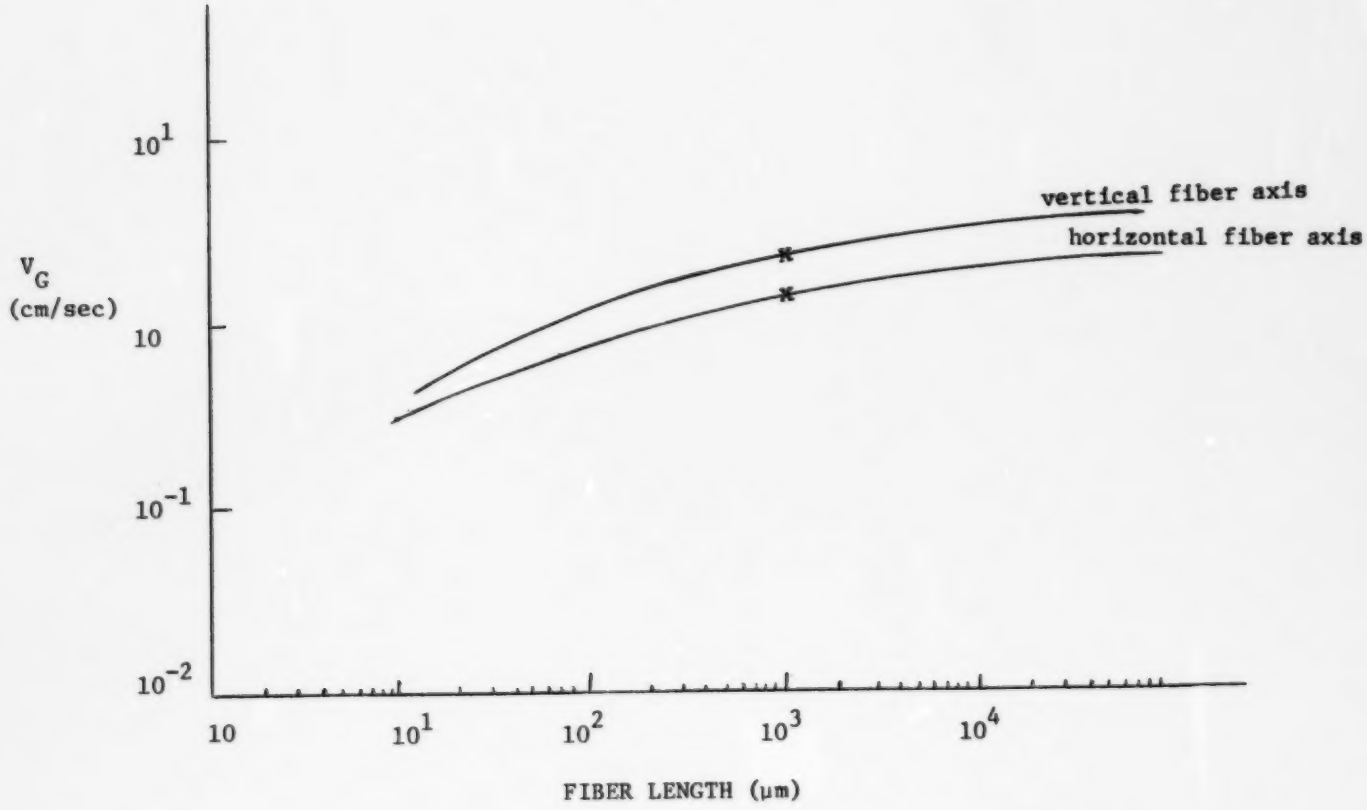


Figure 10. Gravitational settling velocity of CF versus length.

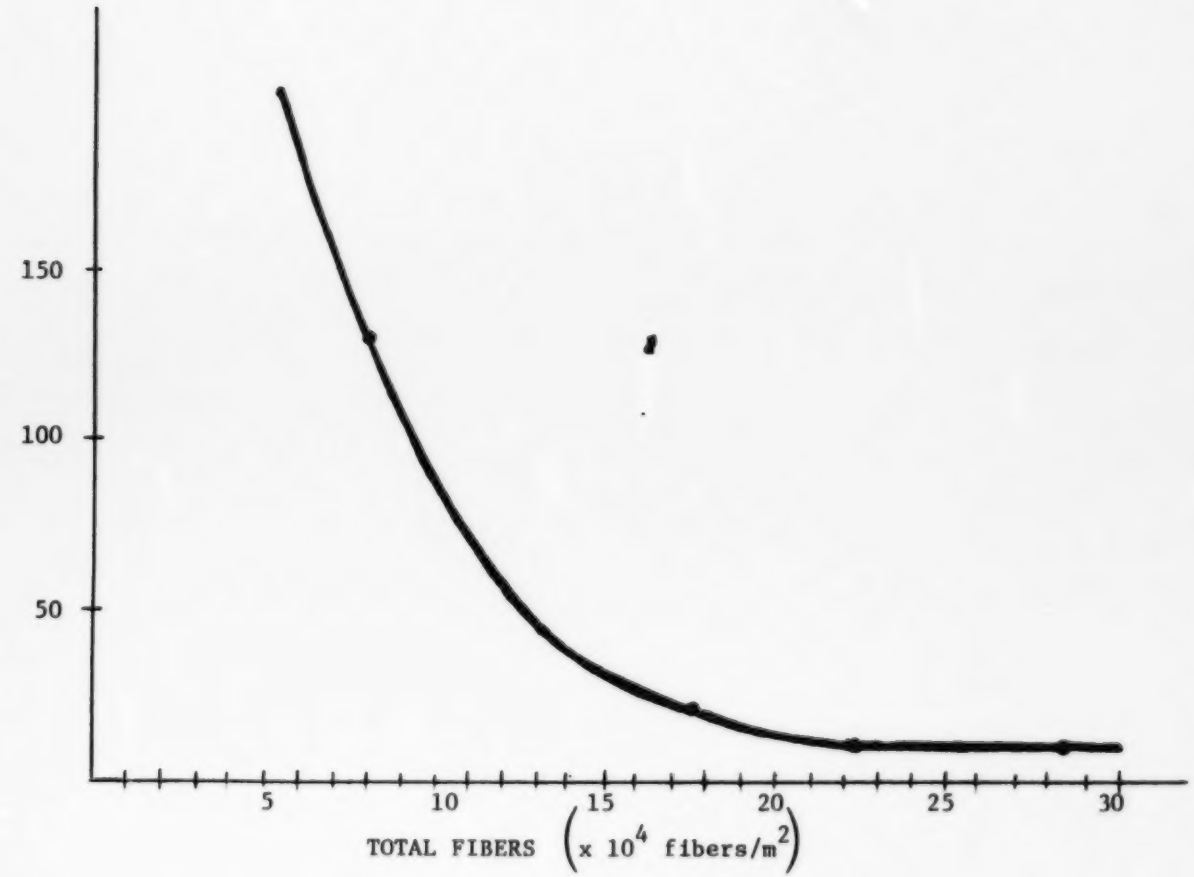


Figure 11. Total fibers as a function of arrival time.

TABLE 8. FIBER DISTRIBUTION AND TOTALS FOR TEST RUNS 81/23-1 THROUGH 81/23-4

Test run 81/23 - x x = ____	≤1 mm (10^4 fibers/m^2)	2 mm (10^4 fibers/m^2)	3 mm (10^4 fibers/m^2)	4 mm (10^4 fibers/m^2)	5 mm (10^4 fibers/m^2)	Total (10^4 fibers/m^2)
1	3.6	2.2	1.0	1.6	Negligible	8.4
2	11.5	3.9	2.6	4.4	—	22.4
3	8.9	3.0	1.9	3.7	Negligible	17.5
4	13.6	4.8	4.5	5.5	Negligible	28.4
5	4.6	1.4	1.0	4.2	—	11.2

TABLE 9. CARBON FIBER SOURCE

TECHNICAL INFORMATION

UNION CARBIDE CORPORATION
CARBON PRODUCTS DIVISION
270 Park Avenue, New York, N.Y. 10017

BULLETIN NO 485-243

"THORNEL" 300 CARBON FIBER GRADE WYP 6 1/0

DESCRIPTION

"Thornel" 300 Carbon Fiber Grade WYP 6 1/0 is a continuous length, high strength, high modulus fiber consisting of 15,000 filaments in a one-ply construction. The fiber surface has been treated to increase the interlaminar shear strength in a resin matrix composite. "Thornel" 300 fiber, coated with a resin-compatible sizing, produces composites with typical shear strength in excess of 13,000 lb/in² (89.6 MPa).

TYPICAL PROPERTIES AND CHARACTERISTICS "THORNEL" FIBER GRADE WYP 6 1/0

PROPERTY	U.S. CUSTOMARY UNITS — VALUE		S.I. UNITS — VALUE	
Tensile Strength	lb/in² x 10³	440	GPa	3.03
Tensile Modulus	lb/in² x 10⁶	33.1	GPa	228
Density	lb/in³	0.064	Mg/m³	1.78
Filament Diameter	μ	7	μm	7
Elongation at Break	%	1.3	%	1.3
Elastic Recovery	%	100	%	100
Carbon Assay	%	92	%	92
Surface Area	m²/g	1	m²/g	1
Thermal Conductivity	BTU-ft/hr(ft²)(°F)	5	W/m K	8.5
Electrical Resistivity	Ohm-cm x 10⁻⁴	18	μohm-m	18
Longitudinal CTE at 70°F (21°C)	PPM/°F	−0.3	PPM/K	−0.5
Specific Heat at 70°F (21°C)	BTU/lb°F	0.23	J/kg K	950

TYPICAL STRAND PROPERTIES "THORNEL" FIBER GRADE WYP 6 1/0

PROPERTY	U.S. CUSTOMARY UNITS — VALUE		S.I. UNITS — VALUE	
Yield	yd/lb	550	m/g	1.11
Denier	g/9000m	8120	g/9000m	8120
Twist	tpf	0	tpm	0
Filaments/Strand	—	15,000	—	15,000
Fiber Area in Yarn Cross Section	in² x 10⁻⁶	78.5	mm²	0.506

The T-300 fibers obtained for the tests were chopped and their length distribution was very uniform, as shown in Figure 12. It may be so observed that the fiber pretreatment and turbulence injection resulted in significant fiber fractionation. Figures 13 through 17 illustrate the size distribution of the fibers in test runs 1 through 5 for a given day. (These runs were the most representative of all test runs performed, and they were made the morning of the final day of testing.)

Test Run 5 shows an abnormally high concentration of the smaller fibers. This is explained by the fact that this fiber loading was obtained from the last of a batch of pretreated fibers. They had been manipulated more than other batches, thus contained a higher number of fractured fibers. Failure to obtain one of the vital parameters of Test Run No. 5 resulted in its being excluded from data evaluation; however, for reference Figure 18 provides the information as related to the fiber charge (loading fall rate). Figure 19 presents the composite of Test Runs 1 through 4 fiber distribution.

TEST RESULTS

Each test run produced a fiber concentration and distribution according to the output of a) actual microscopic counts, b) an electronic count number, c) strip chart recording, and d) a dc signal stored by a magnetic tape recorder. The readings from the strip chart, together with the data obtained by fiber counts, were principally utilized to verify instrument performance. The electronic counter developed a malfunction and, since it was not an essential peripheral, was excluded.

Test runs performed on December 23 were utilized for data results. These runs were made sequentially with no equipment adjustments between runs; room conditions were constant. The testing was performed in a room directly under a large plasma separation unit. Throughout testing the large magnetic fields created by these units would override the oscilloscope traces. Although measurements by the sensor were apparently not affected by these fields, the extensive cabling utilized by this breadboard's peripherals at times experienced transients due to currents induced by these fields. The operation was apparently suspended from testing on December 23, therefore the data from the CF tests on this day were utilized.

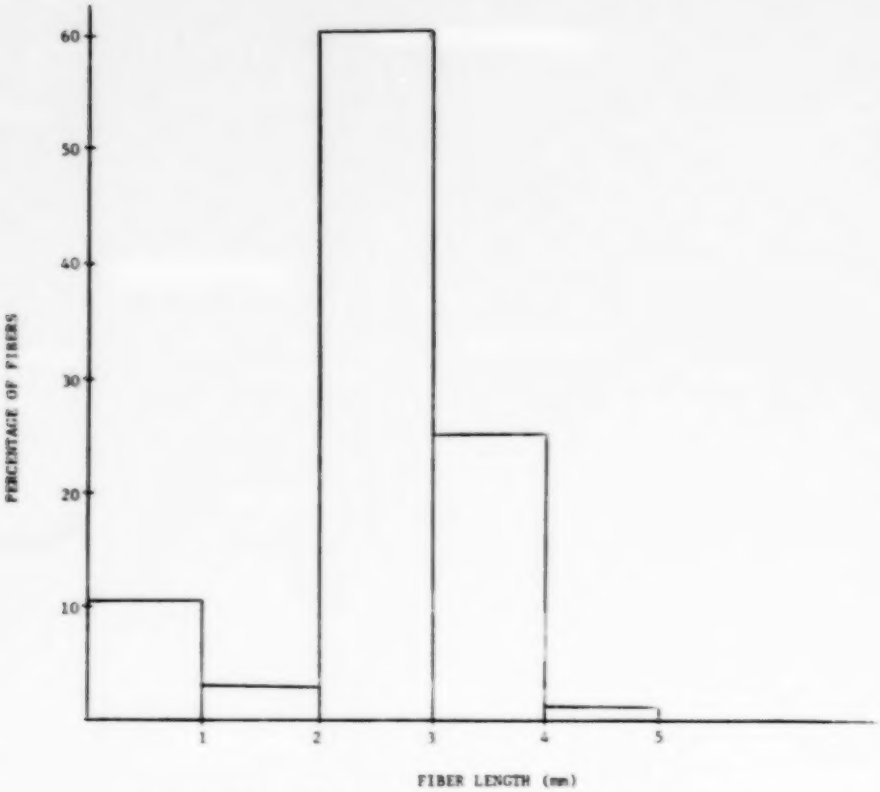


Figure 12. Chopped, "untreated" fiber length distribution.

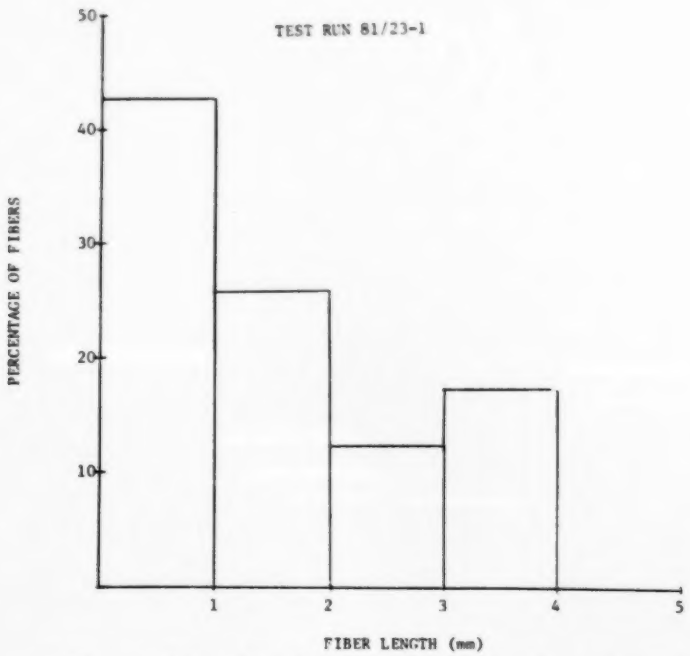


Figure 13. Single fiber length distribution: Test 81/23-1.

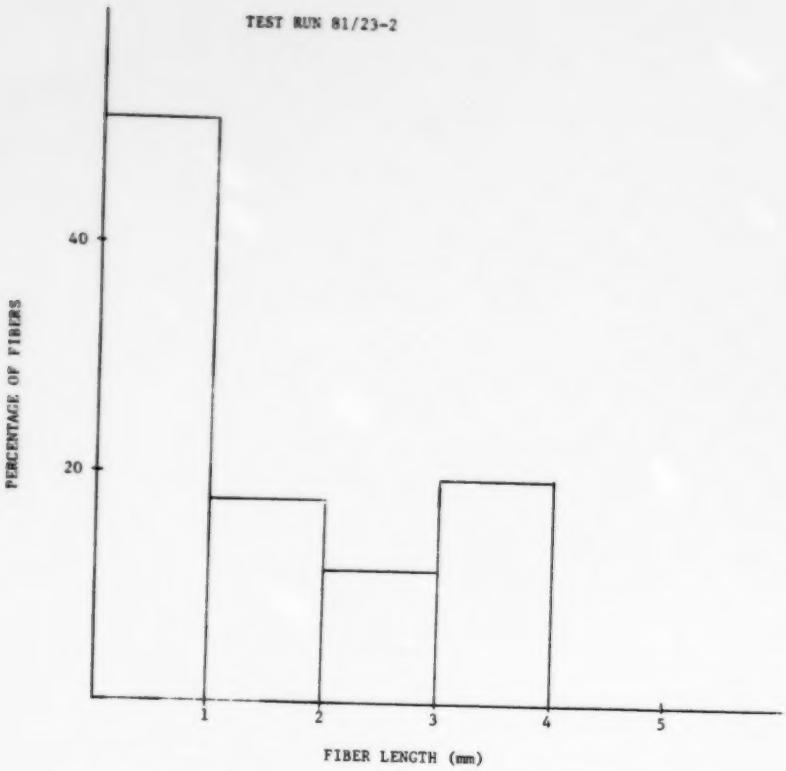


Figure 14. Single fiber length distribution: Test 81/23-2.

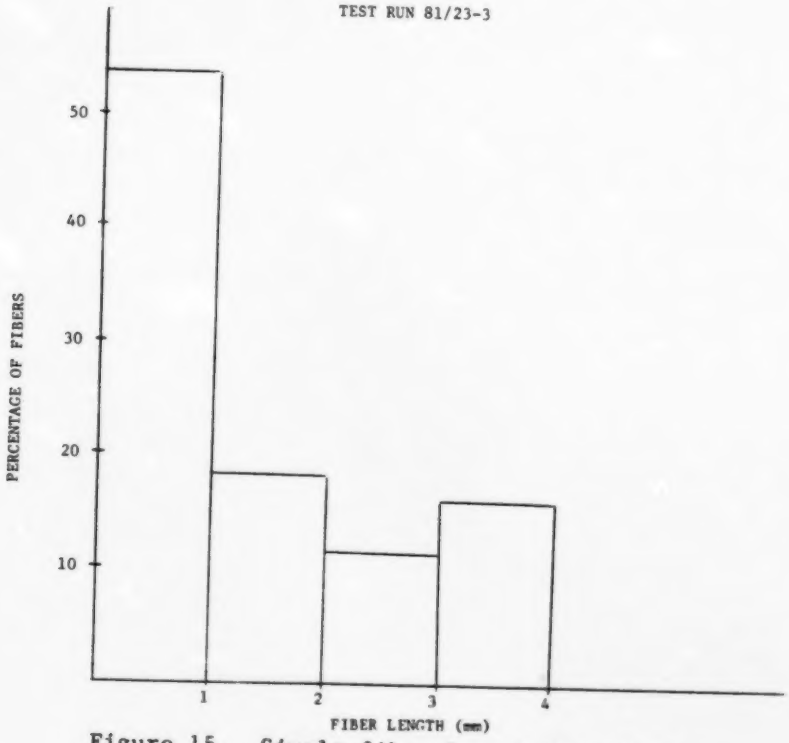


Figure 15. Single fiber length distribution: Test 81/23-3.

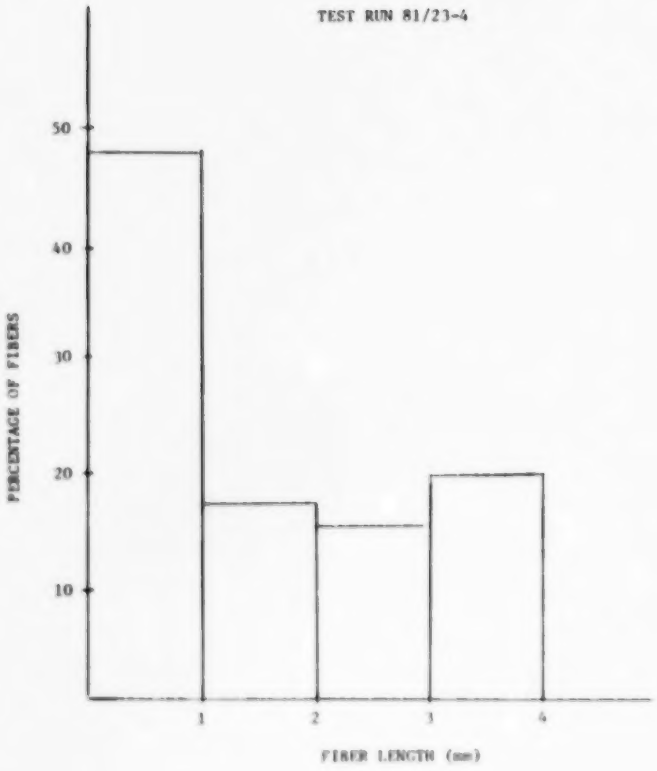


Figure 16. Single fiber length distribution: Test 81/23-4.

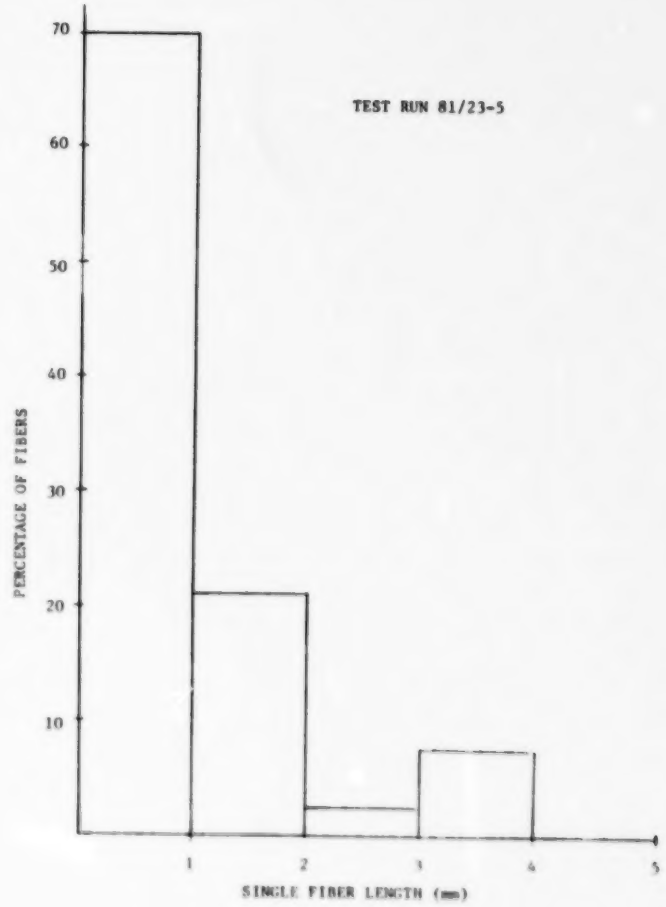


Figure 17. Fiber length distribution: Test 81/23-5.

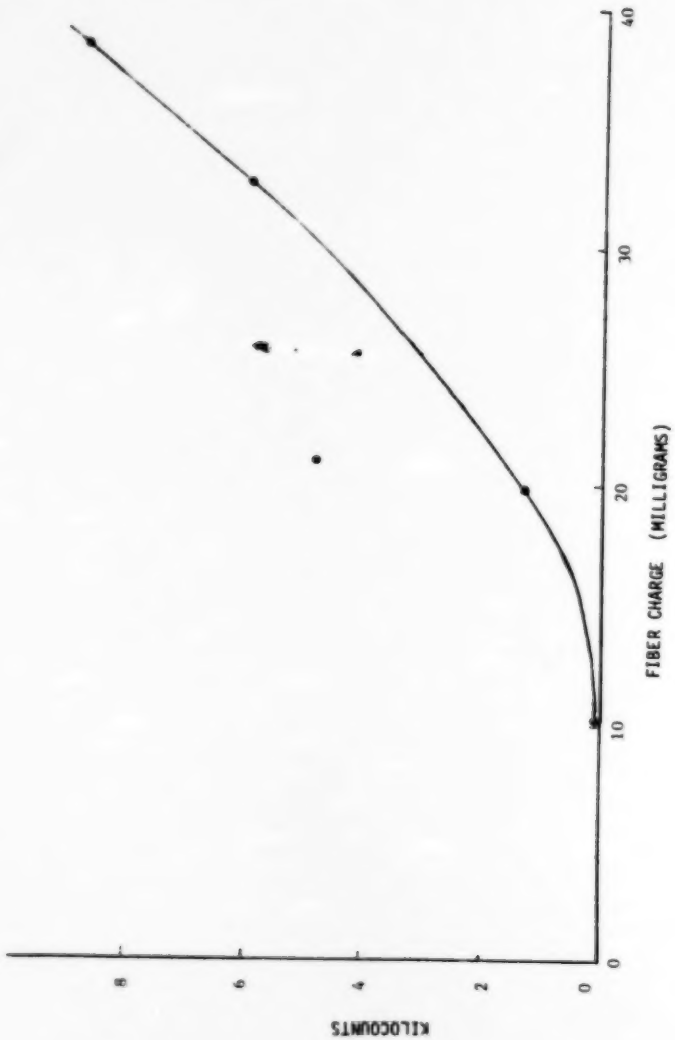


Figure 18. Total counts recorded as a function of fiber mass.

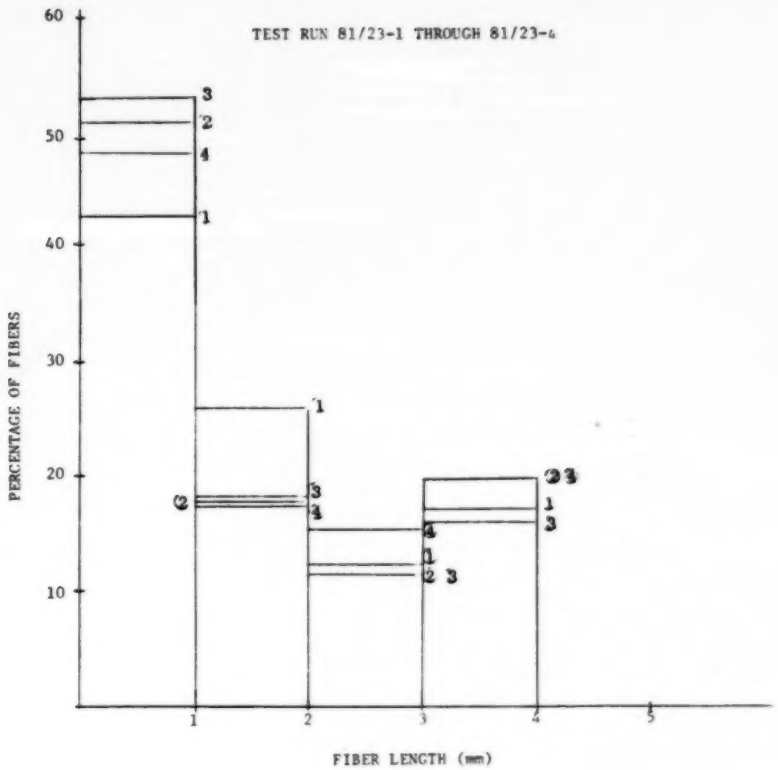


Figure 19. Single fiber length distribution: Composite, tests 81/23-1.

It should be noted that the final electronic design should include features which would alleviate the effects of such field phenomena. Such design features represent no unusual techniques.

Table 8 provided the data obtained by fiber counts for runs 1 through 5. Figures 20 through 25 provide the graphics for the test run information. The data were compared to the data from the sensor (obtained from the strip chart time history). Figure 26 displays such recordings, while Table 10 presents information from these records.

The test runs were also performed with a) only an airstream (no particulate fiber), b) an injected water mist (no particulate fiber), and c) water mist CF present. No effect was seen by the monitor. Although past data provides no evidence that CFs absorb any considerable moisture, studies have shown that the graphite/epoxy composites do (Reference 8). Such moisture variance affects the materials electrical transverse conductivity (e.g., perpendicular to the length; Figures 27 and 28). This suspicion together with unexplained variances in preliminary test runs, prompted a moisture curve analysis and experiments in several pretreatment procedures. It was concluded that any effects at lower concentrations would be lost in the noise of the instrument, while at higher fiber concentrations such discrepancies are statistically accounted for by the calibration procedure. Therefore, no further attention is necessary to adjust for this phenomena.

The reference oscillator throughout testing was set at 516 kHz. This harmonic was selected because it yielded the least interferences. However, this frequency should be selected during prototype development to allow proper tuning of the system.

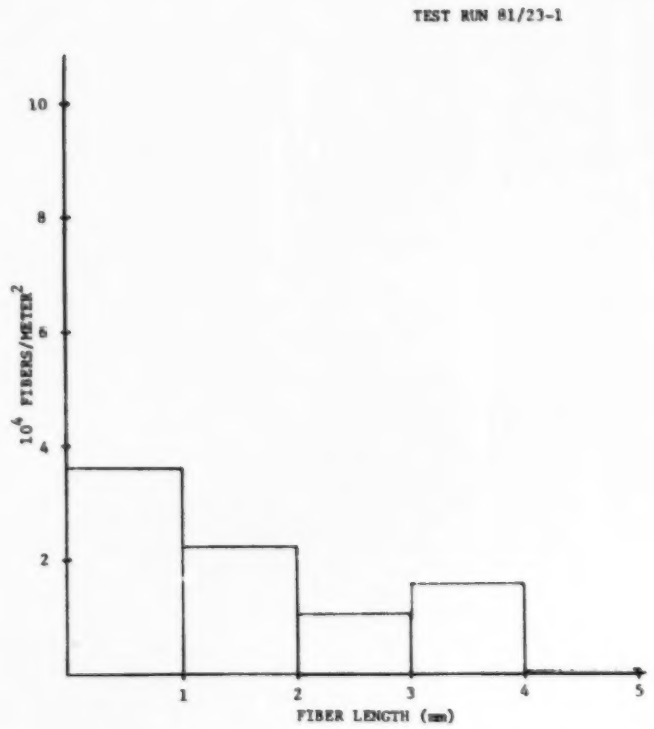


Figure 20. Fiber count as a function of fiber length: Test run 81/23-1.

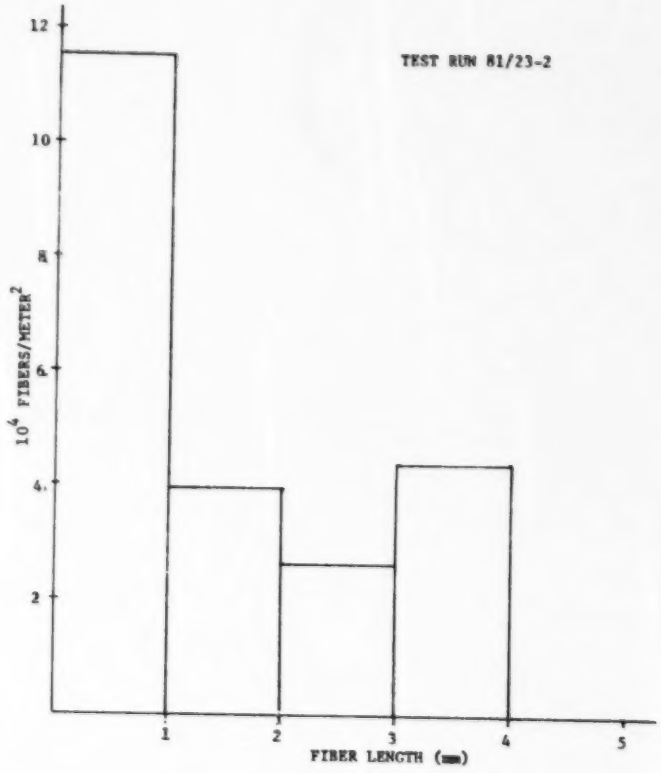


Figure 21. Fiber count as a function of fiber length: Test run 81/23-2.

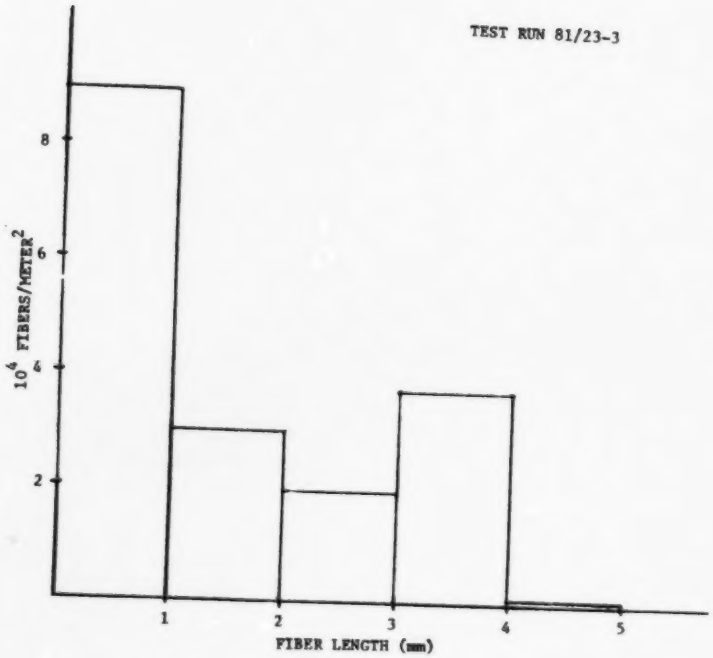


Figure 22. Fiber count as a function of fiber length: Test run 81/23-3.

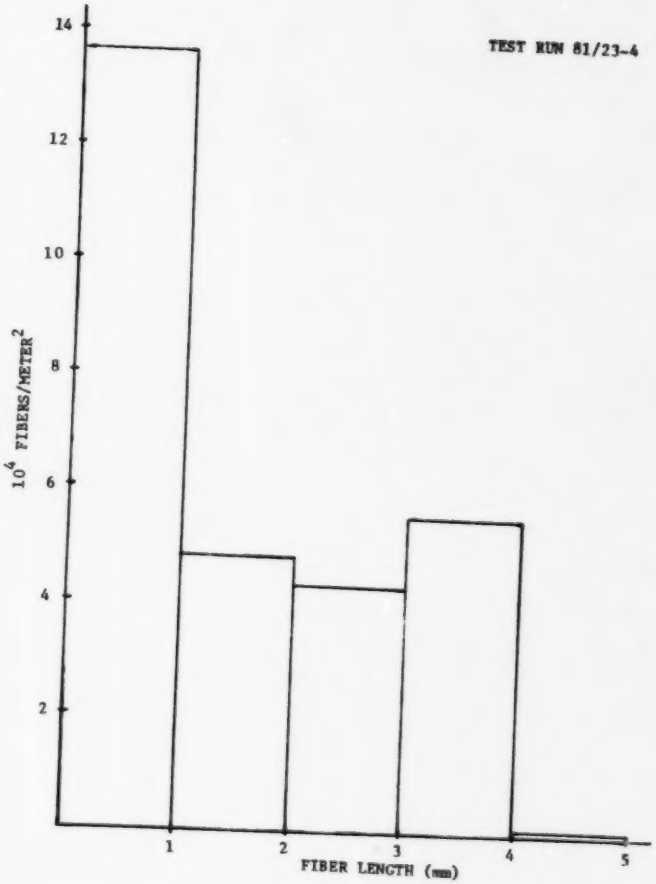


Figure 23. Fiber count as a function of fiber length: Test run 81/23-4.

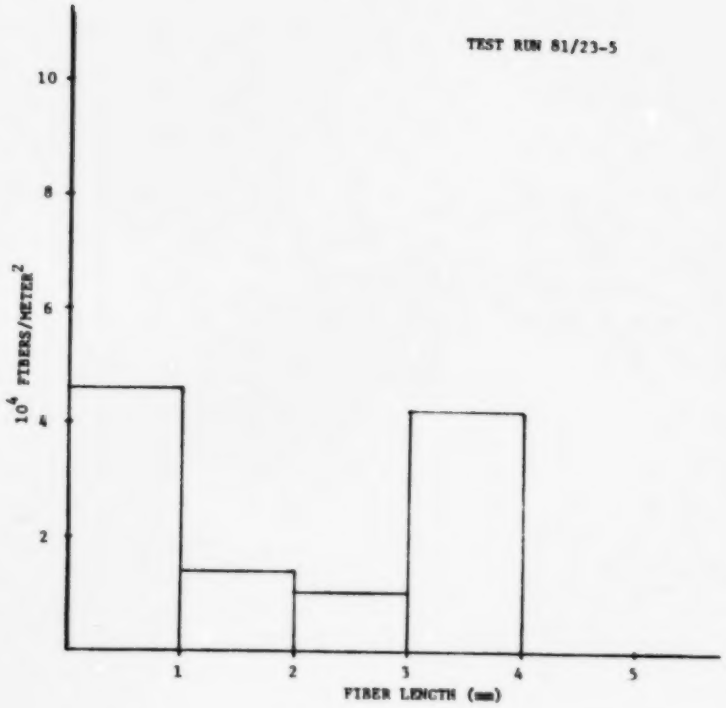


Figure 24. Fiber count as a function of fiber length: Test run 81/23-5.

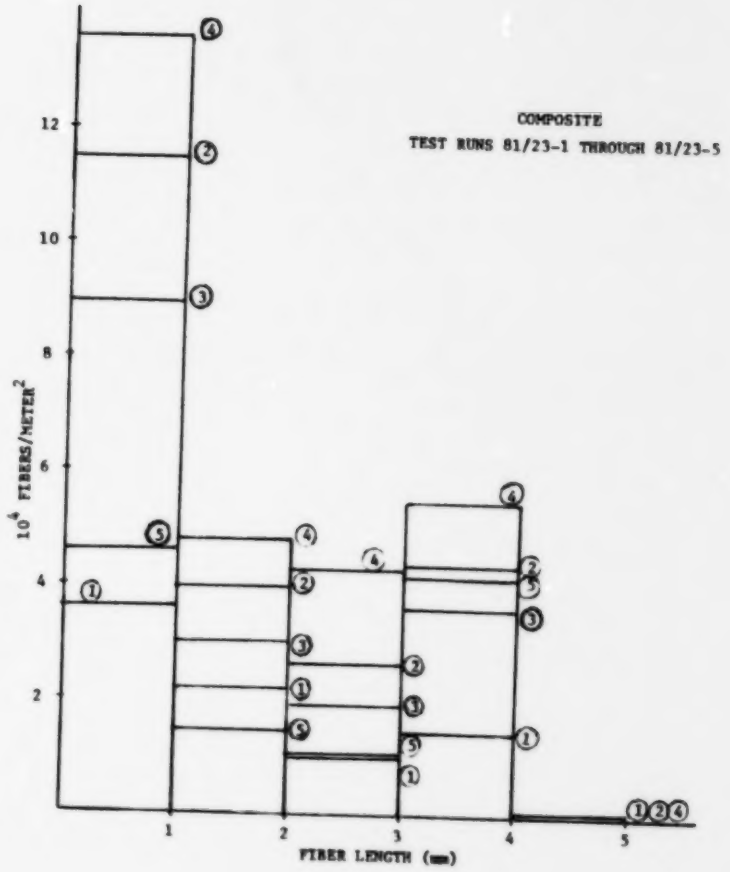
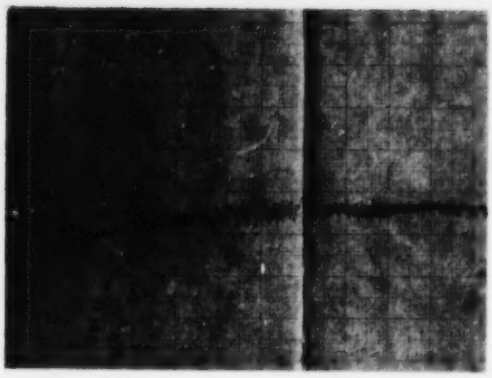


Figure 25. Fiber count as a function of fiber length: Composite, test runs 81/23-1 through 81/23-5.



a. Strip chart record for test 81/23-2.

b. (5 millivolts strip chart) settling which saturates the recorder.

Figure 26. Examples of strip chart records.

TABLE 10. STRIP CHART RESULTS OF TEST RUNS 81/23-1 THROUGH 81/23-4

Test run	Time (sec)	Amplitude (Lines)	Total Mass Loading
1	127	0	
	130	1.5	8.4×10^4 fibers
	150	5.0	
3	20	0	
	30	4.5	
	40	7.0	17.5×10^4 fibers
	36	10.0	
2	10	0	
	20	11	
	30	8	22.4×10^4 fibers
	40	7	
	50	5	
4	10	0	
	15	5	
	20	17	
	25	25	28.4×10^4 fibers
	30	29	
	35	29	
	62	29	
	64	0	

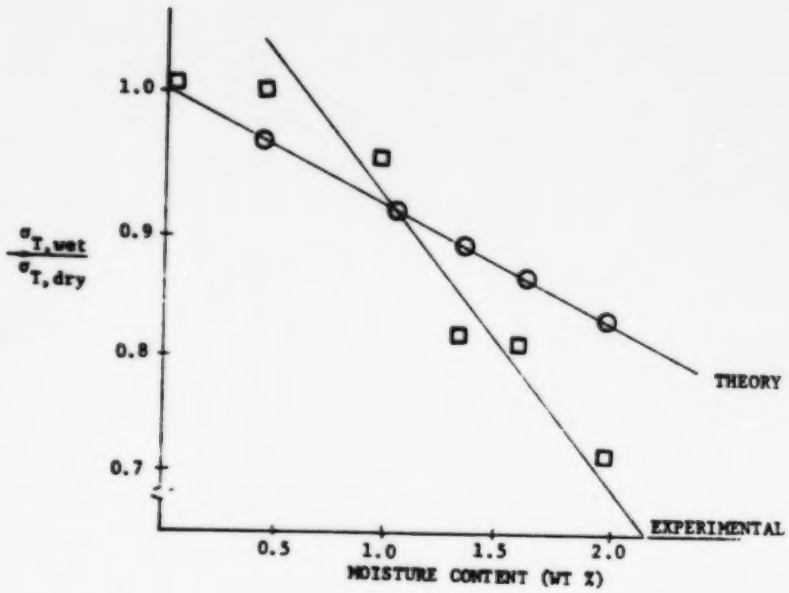


Figure 27. Moisture absorption effects comparison graphite/epoxy transverse conductivity (Ref. 8).

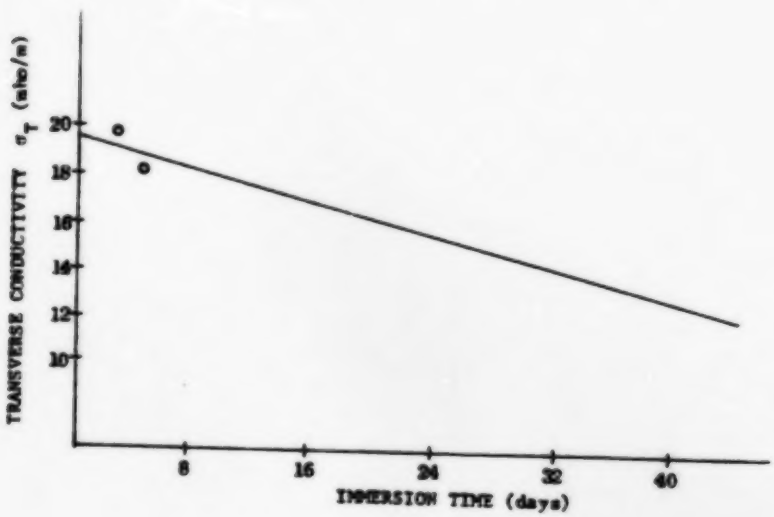


Figure 28. Moisture effects on transverse conductivity (Ref. 8).

Results of the test runs are expressed as amplitude versus fiber concentration in Figure 29. As can be seen the ΔC response is linear. However, when coupled with the ΔR effect a double integral effect is seen at high concentrations. This effect was seen moving the high concentration point off scale where the previously expressed electronic limitations inhibit continued response.

The high concentration fourth run should have shown an output amplitude of 14. It showed 29. This indicates that half of the shift was due to ΔR. If the resistance measuring device had been in the circuit this would have been detected. Following the placement of a cleaning mechanism into the system in the next stage of development, the unit should be tested to achieve a proper calibration of the ΔC with $R = 0$ as well as $R = \infty$ effects. This information together with the ΔR effects will allow proper alignment of the final calibration established with $\Delta R + \Delta C$ variations. Once established these mathematical expressions will remain consistent. Therefore, following prototype development and calibration the unit should require little adjustment or operational and maintenance attention.

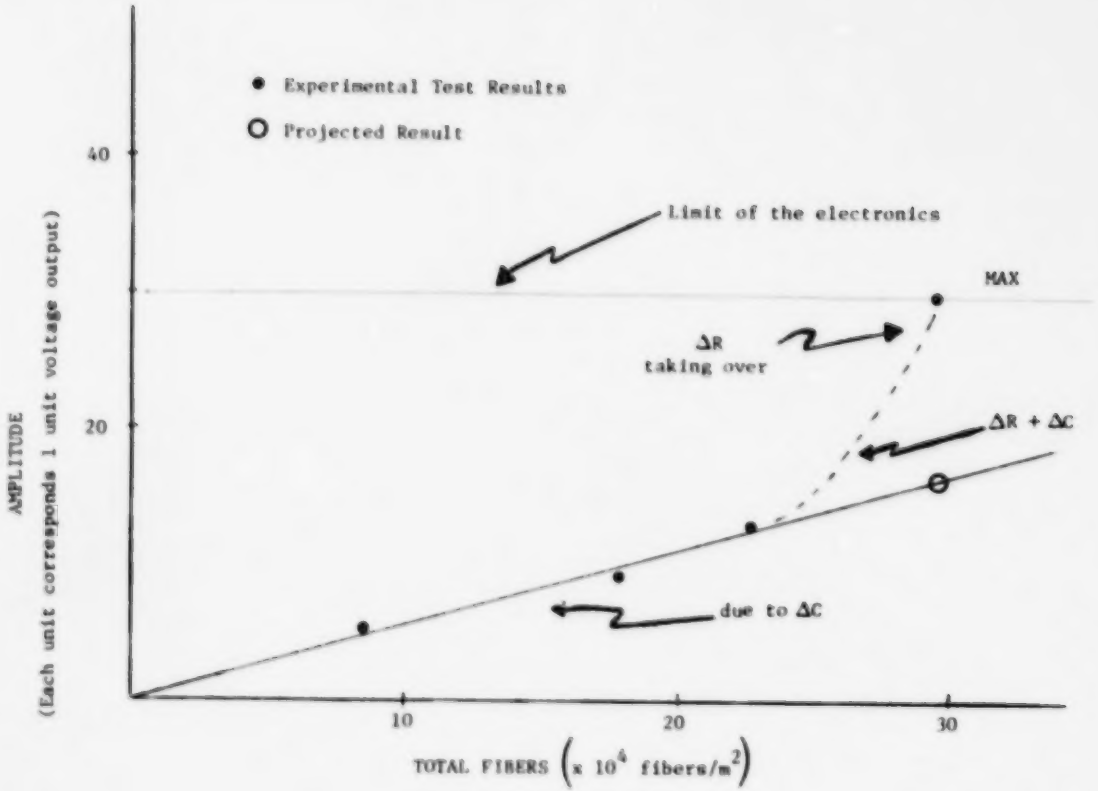


Figure 29. Test results obtained for test runs 81/23-1 through 81/23-4.

SECTION 6

DISCUSSION

This section is provided to clarify many of the issues surrounding the instrument. Since it is a breadboard designed to provide concept validity, there are many indicated changes which should be incorporated into the next development stage to optimize the system and make it a self-contained unit. A discussion of obvious design requirements (i.e., inclusion of a power supply, bandpass filters, a readout device, material selection, etc.) is not included. These are standard design considerations and need not be discussed.

Before covering each of the design modifications individually, a brief discussion surrounding the difficulties of the development of such a continuous monitor is in order.

PROBLEMS FACING NEW CF INSTRUMENTATION DEVELOPMENT

A review of Table 2 indicates several methods have been explored. All instruments accomplish their intended function; however, in each instance, they have severe limitations.

Due to their nature, carbon fibers are inherently difficult to identify and monitor on a real-time basis. Carbon is a major chemical constituent of many of today's compounds, and certainly is unfailingly evident in nature. It is possible to identify particulate materials, even specify when they are fiberous, but to absolutely identify them as carbon fibers requires much more sophistication.

One major problem facing instrument development is reliability. Carbon fibers due to their size, specific gravity, conductivity, etc., possess an affinity for clumping. It is difficult to differentiate two 4 mm fibers from one 6 to 8 mm fiber. Thus due to the large number of fibers released, a significant percentage of error may be introduced.

Also, carbon fibers are often fractured when impacting the sides of ducting, vents, or stacks. Therefore, 5 mm fibers at one point in the air stream may not be the same length at another point.

The environment in which the instrument is desired to function also complicates the issue. Many instruments which have been used in the past are sensitive to vibration or are delicately calibrated. The corrosive, dust, and soot-laden environments certainly pose a problem for all techniques.

INSTRUMENT OPTIMIZATION

The following modifications appear fundamental to the further development of the instrument.

1. Broadband F/V Converter. The present F/V converter has been temporary from the outset. The F/V should be changed to one which will support a much broader frequency band. This will allow for an increase in the dynamic range (thus operational range) of the instrument. Associated with this will be the changes made in the electronics due to the F/V utilized for testing. Increase the response range of the circuit by releaving the limitations placed on the electronics response range in the C_6 and C_7 areas of the electrical circuit (Figure 2). These restrictions are not necessary in a prototype unit and will limit the upper range of the system. (They need not be removed to yield a functional unit.)

2. Modification at the Discriminator Junction (where $f_1 + f_2 = f_3$ is evaluated). The sophistication of the electronics' discriminating function could be improved by the conversion of the reference oscillator frequency of f_2 to f_3 at the junction where $f_1 + f_2 = f_3$ is evaluated. This would allow certain stability and signal-to-noise advantages.

3. Self-Cleaning Device. At a minimum, the circuitry must incorporate a cleaning device to prevent particulate material from accumulating on the variable capacitor plates. This could be easily accomplished by providing a capacitive storage in the circuit which could discharge across the plates at a predetermined time. The decision of when the capacitor should discharge could be determined by the R • C time constant, or by the incorporation of a small microprocessor (see Item 6 below).

4. Circuitry to Measure R (resistance). Data indicate that the system is measuring change in capacitance as well as change in resistance. Thus with proper development R could provide an input to information regarding fiber diameter. Since the conductivity for carbon can be assumed, the directly shunted fibers provide an indication as to the diameter of the fiber. Once the resistance is measured, the fiber diameter can be calculated from the equation:

$$d = 2\sqrt{\frac{\rho \ell}{\pi R}} = 1.128\sqrt{\frac{\rho \ell}{R}}$$

Where ρ is resistivity, ℓ is plate spacing, and R is resistance of the fiber. Thus a mass concentration and information to the fiber diameters is provided.

5. Fiber Length. The determination of the length of the fibers passing through the sensing capacitor may be obtained by the use of additional variable capacitors. If the unit incorporates possibly a set of three sensors, each with a different plate spacing (the plate spacing decreasing as you move down the air stream), a determination could be made as to the fiber lengths. If a microprocessor is included (Item 6), the microprocessor could input the plate spacing information and the distance between each sensor. Once this is known the variations between sensors could provide a description of the fiber lengths (resultant of the overlapping of the sensors' sensitivities) as well as fiber velocities.

6. Microprocessor. A microprocessor would greatly enhance the capabilities of the unit, and although it is not functionally necessary, is highly recommended. An example of its use would be in the decision-making process for determination of the timing of a high voltage discharge across the sensor. The microprocessor could check the frequency shift against the dc current. If f_3 is the reference frequency and f_2 is the frequency shift due to fiber density (D_{F2}) then,

$$f_1 + f_2 = f_3 \quad \underline{\text{yields}} > \text{dc voltage}$$

and

$$f_2 = 2/3 \sqrt{\frac{D_{F2}}{D_{F1}}} \; f_1$$

where f_1 is the frequency shift due to fiber density D_{F1}. Therefore, if D_{F1} is f_1 = 200 Hz and to obtain a 150 kHz shift

$$D_{F2} = \left(\frac{f_2}{f_1}\right)^{3/2} D_{F1} = 2 \times 10^8 \text{ fibers}$$

However, at some point the fibers will short the rings which will give the appearance of an air stream fiber concentration greater than the upper limit of the instrument. (In the case of the test breadboard, this was 2×10^8 fibers/m^3.) Therefore, a check of the frequency shift against the dc current is performed. If R = 0 then there is a short, and if R = ∞ there are 2×10^8 fibers (calculated average diameters of 8 μm) or some combination of fiber lengths and diameter to density.

The presence of a microprocessor also allows several decisions to be made in the electronics such as the ΔC versus ΔR effect. Thus establishing the difference of the effect of fiber diameter and fiber length versus mass. It would also allow the incorporation of some type of chemical or electrical test to evaluate the fibers' carbon specificity. It should be noted that such an instrument may then be utilized to evaluate any conductive particulate material (e.g., boron, aramid, metallics, etc.) in the air stream. Only the values of the known chemical/electrical parameters need be changed in the data base of the microprocessors.

Brief discussions of additional considerations and suggestions are as follows:

a. Due to the increase in the plate size of the capacitors (as you move outward), as you increase the number or the radius of the variable capacitors, you introduce error into the unit. This error may be nulled by varying the electrical connection of the plates from every other plate to every fourth or sixth ring. Connection of the plates in parallel instead of series should also be considered. Such a properly designed combination of connections could produce a variable capacitance which is attributed to the equal contribution of rings regardless of plate size.

b. Normal operational and maintenance procedures should adequately care for the instrument; however, if the monitor is subject to low temperatures or conditions conducive to condensation on the capacitor plates, a preventative mechanism may be desired. The inclusion of a low current source to the sensor should be adequate. This should also aid in keeping the sensor clean by decreasing particle adherence during nonoperational times. Another option would be the triggering of the self-cleaning device immediately upon start-up.

SUMMARY

At the beginning of Section 5, nine questions were presented as objectives of the test sequence. Although most of these have been discussed at some point, a summary is in order.

a. Are individual fibers counted? The current instrument is counting fiber mass and indicating fiber diameters to yield an approximate count of individual fibers.

b. What is the operational range of the device? Its present operational range has a lower limit of 10^4 fibers/m^3, and the upper range is restricted by the absence of a cleaning mechanism and the internal circuitry to an upper bound of 2×10^8 fibers/m^3.

This upper limit has the potential of being greatly increased; however, an improvement on the lower limit is doubtful, due to signal to noise difficulty.

c. Can fiber lengths be established? Currently, fiber length can not be directly recorded. Only an approximation may be made based upon the dc shift and the known ring spacing. Again, the recommendations for further development included the design engineers' suggestions of how this issue may be addressed.

d. How small/large of spacing can be used?

e. How does the sensor's diameter reflect the electronics sensitivity?

f. How does the previous question's answer relate with the plate spacing and fiber lengths?

In each of the preceding questions, the issue was not directly addressed in the testing effort. This was due to the limited scope of this Phase II activity and to the schedule constraints. It may be assumed, however, that the distance of the spacing between the capacitor plates can be varied, but any variance would require changing the values of the components in the circuit. In general, decreasing the spacing distance would increase sensitivity and is limited only by the manufacturing capability. Increasing the distance would act to decrease the sensitivity and would have to be compensated for in the electronic circuitry by increasing gain. Any further conclusions would be premature. The next phase of instrument development should include varying capacitor designs to further explore these issues.

g. What happens to the sensor with no care and maintenance? Normal operational and maintenance procedures will adequately care for the instrument. Once tuned, the instrument should be insensitive to dirt, corrosion, vibration, etc.

h. Will condensation affect its operation? Indications at this point are that condensation will not significantly effect the instrument while continuously operating. However, to prevent start-up problems the cleaning mechanism should be activated initially to evaporate condensation on the concentric rings. If further protection is required, as in cold climates, a low current may be continually supplied across the plates to prevent freezing, etc.

i. Is a cleaned process necessary? Yes, if a cleaning mechanism is not present the capacitor will short as soon as an adequate number of fibers collect across the plates.

One potential problem (in the incinerator environment) for which no immediate solution is seen, is that while carbon black is not a problem itself, if it is accumulating on the entrained noncarbon fibers present in the air stream these non-conductive carbon-coated fibers will appear as conductive 'carbon fiber' to the monitor.* However, since the impact of the ΔR is small the instrument will decrease the percentage of error; nevertheless, error has been injected.

In summary, the work indicates that the instrument shows great promise in providing the information necessary to accomplish its intended function. With today's technological capabilities the final system should be relatively inexpensive, even if a microprocessor is incorporated, as well as easily transported and installed. Also, its mass production cost should not prove prohibitive.

*Since carbon black itself is nonconductive, it is only a problem when associated with an extraneous fiber.

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